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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 2, PP. 55–66, AUGUST, 1942

ACCUMULATION OF DIATOMACEOUS DEPOSITS

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In many natural waters there are laid down deposits of varied mixtures of materials; in other waters, conditions are such that a single material is deposited in considerable purity, while in still other waters various materials, segregated through slight differences in their physico-chemical properties are ultimately deposited in high concentration in separate locations. The two former methods apply chiefly to lakes, while the latter operates more effectively in large bodies of water such as the oceans.

The mixed types of sediments may find comparatively little use because of the conflicting properties of their various constituents, whereas any relatively pure sediment is certain sooner or later to attain commercial value in specific applications of economic or industrial importance based on its special properties.

It is such pure deposits, too, which offer perhaps the most favorable opportunity for study of the conditions and principles of the sedimentary process, for in them the complication of factors which accompanies miscellaneous deposition is reduced to a minimum of simplicity and directness. Hence, we shall choose to limit ourselves here to discussion of the purer type of deposits, and of the diatomaceous deposits in particular.

Furthermore, diatoms offer, as index fossils in the study of sediments, certain definite advantages, which deserve mention: a) almost univerally present in natural waters, both fresh and marine, and often in considerable numbers, they afford good criteria for comparison, b) once formed, and especially once deposited, their shells, being of pure silica, are very stable, c) they possess a characteristic structure which is easily recognizable, and d) they occur in a wide array of species and varieties, many of which have somewhat definite ecological requirements, which quality gives them value as a reliable clue to conditions that may have prevailed at any particular stage of deposition.

OCCURRENCE AND SIGNIFICANCE

Vast exposed beds of highly pure diatomaceous earth in the western United States, and in many other previously submerged areas of the world, give impressive evidence of the dynamic character and long duration of conditions suitable to this particular type of deposition. Some of these beds range in thickness from a few to hundreds of feet, or in certain instances to more than a thousand feet. Some exhibit an undifferentiated, snow-white appearance with uniform texture throughout; others reveal a distinct stratification into almost paper-thin layers, distinguished by alternate variations in color from yellow or gray to brown, by changes in floristic content, and by detectable variations in compactness of texture. At certain levels they may give place to thin intrusions of volcanic ash or flint, or strata of fossilized fish skeletons, representing a temporary cataclystic interruption of the even tenor of deposition. Both the highly homogeneous and the stratified deposits bespeak the long continuing geological periods of unchanging equilibria of the aquatic environment which exclusively favored such sedimentation. The purity of these materials may reach as high as 94 to 98 per cent silica, entirely in the form of diatom shells; the remaining 6 to 2 per

cent consisting of traces of iron, organic matter, of alumina as clay, or possibly of a slight amount of carbonate.

Nor is this process a relic of Miocene times when it reached its height in marine waters, or of Pleistocene time when many fresh-water deposits were formed, but it is going on today in many lakes and in certain large areas of the oceans where the proper combination of conditions obtains. Obviously, as suggested, by a comparison of lakes or regions where pure diatomaceous deposition is in progress, with others where mixture of sediments occurs, it is possible largely to determine the ideal set of factors that governs accumulation of this one type of sediment, and to learn some principles of the sedimentary process.

For convenience of access, and range of variability of topographic features and of physico-chemical conditions, the lakes of the concentrated lake district of north-central Wisconsin, proved peculiarly well situated for pursuit of such investigations. Among lakes in close proximity, yet widely different as to the chemical composition of their waters, can be found some whose sediments are dominated by either clay, lime, organic matter (pollen and lignins), or are purely diatomaceous. Much advantage is also afforded by records of detailed physical and chemical studies made on these lakes by Birge and Juday and their co-workers. Of the diatomaceous silica depositing lakes, it is possible to select a few whose crude sediments will yield as high as 60 to 75 per cent silica entirely as diatoms, the remaining portion being organic matter associated with the diatoms. Such sediments dry with a light gray to almost white appearance, very light weight, and a friable texture. In environments productive of such sediments the conditions of diatomaceous deposition are probably as uninvolved and direct as can be had.*

* Investigation aided in part by the Brittingham Fund of the University of Wisconsin, and facilities of the Trout Lake Limnological Laboratory of the University.

GENERAL CONDITIONS OF DIATOMACEOUS DEPOSITION

What would clearly seem a simple and straight-forward process is by no means as easy of interpretation as might at first appear. It soon becomes evident to the investigator that, however similar or apparently identical certain bodies of water may be, there are no two deposits, nor even two levels in the same deposit, which are exactly alike, as to their components, their rate of accumulation, or other features. Before attempting a consideration of the variables involved it might be well to review briefly the general conditions of formation of concentrated diatomaceous deposits.

The requirements for diatomaceous deposition may be conveniently divided into two categories, namely:

1. Conditions favorable to diatom growth.
2. Conditions governing the exclusion or subsequent elimination of all other materials.

CONDITIONS FAVORABLE TO DIATOM GROWTH

It is axiomatic that for the production of diatomaceous sediments, conditions favoring diatom growth are necessary, and that the more suitable are these conditions, the more accelerated will be the accumulation of the sediments. Congenial environmental conditions constitute a postive factor, and include basically the proper illumination, so necessary to all phytoplankton, diatom, or micro-algal growth. This need only be mentioned, as being generally present at varying levels in all relatively clear lake or ocean waters. Supplementing this there must be an ample supply of the proper nutrient solutes in the water, with emphasis upon a plentiful supply of silica which is, of course, the basic material of the potential sediments.

Of the physical environmental factors, low temperature not only favors diatom growth by inhibiting bacterial activity, thus keeping down acidity resulting from decomposition processes, and avoiding

surface disturbances and flocculating effects to the diatom cells, but it is also generally recognized as optimal to diatom metabolism. A number of authors have suggested the beneficial effect to diatoms of the higher trihydrol content of cold waters coming from melting ice. The capacity of colder waters to absorb and carry larger amounts of both dissolved oxygen and carbon-dioxide is experimentally demonstrable as greatly favoring diatom growth. In this respect the northern lake waters, and waters of alpine origin, are distinctly advantageous. The whole matter of low temperature is quite clearly associated with the higher diatom productivity of the northern and deeper lakes, of high altitude waters, and of the temperate and frigid oceanic areas.

Acidity, or hydrogen-ion concentration, is another significant factor in the diatom environment. Diatoms appear definitely favored in general by an approximately neutral or slightly alkaline pH, which may act both directly in their physiological processes, and indirectly in connection with the chemical equilibrium of the aquatic environment. Strong acidity suppresses the diatom flora and is likely to favor accumulation of undecomposed ligneous sediments; while a high alkalinity retards growth and is usually associated with a super-abundance of lime resulting in the accumulation of mixed carbonaceous sediments. Although excessive amounts of carbonate are detrimental to formation of pure diatomaceous deposits, it is well known that small amounts of both lime and magnesia are essential to diatom growth. These substances seem to occur in such suitable amounts in the lakes under discussion, which lie in glacially formed siliceous-sand basins, and which receive but slight drainage from carbonate rock or soils. The same principle applies to lakes in craters or igneous rock basins of the West and similar regions.

Of the soluble nutrients, those most commonly mentioned as possible limiting factors to diatom growth are phosphates and nitrates. Although these are meager, and at any given time are present in the water in exceedingly minute quantities, in the writer's experience they are recurrently soluble or generally available in sufficient quantity to care for normal diatom productivity, other conditions being comparable. In fact, studies of the northern Wisconsin lakes strongly support the conclusion that low amounts of these particular nutrients give a competitive preference to diatoms over other micro-floristic constituents. In lakes where larger amounts were available, other micro-algal forms appeared to flourish, with more rapid decomposition processes, resultant higher acidity, and other conditions giving them supremacy over the diatoms.

Of all the nutrient factors, perhaps that one which is most frequently overlooked as to its bearing on the limitation of diatom productivity is silica. Although this substance seldom appears to be deficient as compared with nitrates and phosphates, there almost invariably seems a direct relation between its abundance and amount of diatom productivity, with, naturally, a considerable significance to the rapidity of accumulation of deposits. However, the amount present in a body of water at any given time is not entirely indicative of its availability, or of the capacity of the diatoms to utilize it. The northern lakes afforded splendid opportunity for examination of these relations. In some lakes silica is meagerly supplied by the drainage system and correspondingly slowly utilized by a light diatom growth, so that the amount analyzable in the water is not unlike that in another lake richly supplied but also supporting a heavy diatom growth that efficiently uses it up. In the latter, naturally, the sediments must either accumulate more rapidly or contain a greater proportion of diatomaceous silica. In other waters the silica supply is so abundant that the amount present is always excessive, in spite of the presence of a luxurious diatom growth, which seems utterly incapable of utilizing the silica available, although apparently

amply supplied with all other normal requisites. From the studies made it may be said, in general, that those lakes whose waters showed a silica content of less than 1 part per million of water supported a rather light diatom flora and had sediments with a minor proportion of diatoms; lakes with a silica content of from 1 to 4 or 5 p.p.m. show a medium to rich diatom productivity with frequently rich diatomaceous sediments, and waters of from 5 to 16 or 20 p.p.m. of silica have a heavy diatom flora with the silica always much in excess of capacity for its utilization, and with frequently quite pure and highly concentrated diatomaceous deposits. The presense of any quantity of silica over 1 part per million at any time may be taken to indicate a more than adequate supply of this substance, and probably implies inability of the diatoms to fully utilize it due to deficiency of some other material, such as phosphates or nitrates, functioning as a limiting factor to their greater development, in accordance with Liebig's Law of the Minimum, which states in substance that the production of a given organism is governed by that material vital to it which is present in a minimal amount. As to their power for extracting silica from the water the diatoms are quite capable of exhausting it down to a very small fraction, because of the exceptionally small amount of this substance needed by the very delicate plankton forms in their cellular structure.

The importance of an abundant supply of dissolved silica to diatom productivity is amply supported, by the heavy production of diatoms in western streams carrying a high dissolved silica content as a result of the drainage of alkaline soils. Meloche and Leader (verbal communication) have shown the best source of dissolved silica to be impure quartz sands subjected to alkaline waters. The idea of this relationship is further corroborated by the popular theory that the richness of western diatomaceous deposits has been due to periodic vulcanism with the consequent enrichment of the waters with silica from the solution of finely divided volcanic dusts. All evidence points to the siderable importance of this factor in the production of diatomaceous deposits.

CONDITIONS GOVERNING PURITY OF DEPOSITION OF DIATOMACEOUS DEPOSITS

The above briefly summarized optima for diatom growth, although a primary necessity for the accumulation of diatomaceous deposits, are of secondary importance to the maintenance of purity or high concentration of these deposits. Given a body of water consistently supporting a diatom flora, however light or heavy the diatom growth, diatom bearing sediments will result, but the purity or concentration of these sediments will depend on the exclusion or the subsequent removal of all contaminating materials.

Materials commonly contaminating diatomaceous deposits are 1) sand, silt, or clay, 2) lime carbonates, 3) iron, 4) ligneous or other organic remains.

The first two categories comprise substances which are stable and are as persistent in the deposits as are the diatom shells themselves, so that they are not removable once deposited. Iron and organic matter, on the other hand, are subject to subsequent removal through solution, chemical action, decomposition, or oxidative processes, leaving the diatom remains intact as a concentrated and homogeneous material.

Obviously from this, pure diatomaceous deposits can accumulate only in waters where the conditions are such that sand, silt, clay, and carbonates are excluded completely from the start. Exclusion of lime carbonates naturally follows in drainage areas free of calcareous rocks and soils, such as are the glacially formed, siliceous-sand basins of the northern lakes, and lake basins in other areas underlain by igneous rocks. Here no lime enters the water to be deposited. Sand, silt, and clay, as insoluble constituents, must be excluded by purely physical means if sediments are to accumulate free of them. Sand is heavy and

ordinarily reaches open water sediments only through swift streams or strong water movements, which are usually absent in small protected lakes, especially of the seepage type. Silt and clay, being lighter, are easily borne by wind and the less vigorous water movements and find their way into deposits except under the most rigorous exclusion. In past ages when most of our fine-grained sediments were laid down, wind borne contamination was doubtless a very minor factor, due to most of the land being protected by vegetation cover. This no longer holds. Silting is naturally commonest in stream fed basins, whereas small seepage lakes with no eroding shores, or with a marginal fringe of wild rice or other large aquatics to sift out any inflowing sediments, offer the protective topography essential to best diatomaceous deposition.

The seepage type of drainage system, particularly as found in abundantly spring-fed lakes in these relatively coarse sand basins, proves ideal for replenishing the silica content of lake waters by the influx of heavy silica-bearing underground waters, containing other nutrients as well. These inflowing waters carry no particulate matter, and hence add no contaminants, as is invariably done by surface drainage.

In crater lakes, or mountain lakes in rock basins with no eroding soils, and fed by small cold streams, very favorable conditions obtain for diatomaceous deposition. In the larger bodies of water, such as the oceans, much the same principles prevail, but segregation of the various sediments is accomplished by selective sorting through water movements and deposition in quieter areas.

A similar problem in connection with the further refinement of some of the lake sediments, which has been recognized but is difficult of solution, is the possible effect of the currents caused by the annual turnover of the lakes in removing the lighter organic elements, and possibly silt, from the very flocculent surface layers of diatom sediments. The strength and disturbing effect of these vertical currents in deeper waters is not known. A striking observation suggesting this, was the frequent noting of distinctly purer diatom sediments in small areas in the deeper parts of many lakes.

CHARACTERISTICS OF DIATOMACEOUS SEDIMENTS

Whether the diatom proportion of a sediment is high or low, the remaining portion being organic matter, the ultimately purified sediment, whether by natural oxidation or by artificial refinement, may be equally good, providing the sediment was formed under conditions for the exclusion of contaminants as described in this paper. The range of proportionate composition of diatomaceous sediments which may be expected to form an end product of high concentration is shown in the following Wisconsin lakes, selected from a larger series, as representing samples covering the extreme range.

	Diatomaceous Silica %	Organic Matter %
Grassy Lake (near Fish Trapp) Vilas Co.	20	80
Irving Lake (near Star Lake Town)	35	65
Spring Bog (near Jute Lake)	73	27
Spring Bog (near St. Germain Lake)	73	27

In fact, paradoxical as it might seem, in the industrial production of diatomaceous earth from diatomaceous peat sediments such as the above, it is often the less concentrated (yet pure as to diatom silica) which are preferred. The reason for this is that the material is refined by combustion of the organic matter, and the peat with a high organic content and lower proportion of diatoms, once ignited becomes self-incinerating, whereas material with a higher than 50 to 55 per cent ash content must be oxidized by forced burning, which is more costly, though the end products may be identical. In Nature the reverse is undoubtedly

true, and the better beds have resulted from the oxidation of originally rich crude sediments in which the diatom content was high and the accompanying organic matter was of the fine textured type from the diatoms themselves, lending itself to ready oxidation. The more heavily lignified organic sediments with a lower proportionate diatom content tend more to remain intact as peat materials, with a considerable corrosion of the diatom constituents.

When free of contaminating and binding materials, such as iron or calcium-carbonate, the texture and physical characteristics of various diatomaceous deposits depend largely on the types of diatoms composing them, which in turn are directly associated with the ecological environmental conditions under which these diatoms lived and which favored one type of diatom flora or another. Thus the coarseness, porosity, compactness, or other qualities of sediment (and incidentally these are the qualities upon which its commercial value may rest) depend much on whether it was formed from light plankton diatoms which settled from open deep waters, or whether it represents the accumulated remains of heavy-shelled epiphytic forms growing in shallow waters richly supplied with silica and other nutrients.

HISTORICAL SIGNIFICANCE

The remarkable thing in connection with the accumulation of large and thick deposits, in view of the exceeding minuteness of the annual increment of material, is the rigid maintenance of the ideal conditions of deposition over great periods of geological time.

It seems unlikely under the disturbing influences accompanying modern widespread utilization of natural resources that the necessary requirements for such pure deposition will continue in the future, except in certain well isolated and protected areas; for, leaving aside the thought of floods, erosion, and major industrial disturbances, it is conceivable that the dust storms resulting from deforestation, cultivation, and removal of vegetation cover may well drop on our natural waters sufficient silt to give a 50 per cent or greater contamination of henceforth accumulating sediments. This is an observation of some conservational significance, but of little economic importance so far as continued accumulation of sediments concerns us, for the available materials are too plentiful, and the rate of accumulation is too slow, to give us much interest in further accumulations from an economic standpoint.

RATE OF ACCUMULATION OF DIATOMACEOUS SEDIMENTS

Much speculation has been offered as to the rate of accumulation of sediments, and interesting and useful though this matter is from several viewpoints, it is clear that no stereotyped figure can express it, and the present knowledge concerning it is scarcely more than conjecture.

Several methods of approach are available:

1. Determination of total thickness of sediment as a function of period of deposition, as established by means of other geological criteria.

2. Direct experimental measurement of accumulating growths or sediments on submerged surfaces.

3. Correlation of a given thickness of sediment with known time intervals marked by definitely determinable and measurable units, such as tree ring series or other chronological indicators and artifacts.

4. Direct counting of differentiated stratified layers.

The first method is perhaps the most reliable to date, and probably as good an opportunity for its application as any is to be had in the northern Wisconsin lakes. In these lakes a clear-cut, coarse-sand basin is overlain with a definite thickness of sediment relatively easy of penetration and accurate measurement. In light of the wide and rapid dispersal of micro-algal forms, it is reasonable to assume that diatom growth and deposition

commenced immediately after formation of these lake basins by glacial action. The indeterminate variable in this case which precludes a rather satisfactory estimate of rate of sedimentation is the question as to the exact lapse of time since the close of glaciation, which at present is placed by geologists at from 30,000 to 50,000 years. As can be seen from the accompanying table the extreme range of thickness of sediments in these lakes is from about 10 feet to somewhat over 40 feet. Taking for convenience a thickness of sediment of 30 feet forming over a period of 30,000 years, we have a rate of formation of 1 foot in a thousand years, 1.20 inches in 100 years, or 0.012 inches in one year. It is easy to appreciate from these figures what a small annual contribution of atmospheric dust would be necessary to give a heavy contamination to such slowly forming sediments.

Lake	Thickness of Sediment	Depth of Water above Sediment
Grassy (near Fish Trapp)	42 feet	10 feet
Irving (near Star Lake town)	?	3
Crystal (near Trout Lake)	10	45
Spring bog (by Jute Lake)	17	1
Spring bog (by St. Germain)	8–10	1

(Irving Lake is similar to Grassy, with coarse, fast accumulating surface sediments; no determination of thickness was made.)

Soper and Obson (1922) give a range of deposition rate of from 0.72 to 2.16 inches in 100 years, which is quite in keeping with the above, and perhaps represents as satisfactory an approximation to actuality as we can expect to attain. At least it seems as close as can be had until Geology can assign a more certain interval for the period since glaciation, and even then there is room for error in careful measurement of thickness of deposits. By taking the various combinations of the figures given above it is obvious that a large range of error is covered, and yet this probability gives a rather good picture of the relative as well as the actual rapidity of the sedimentary process. Gunter and Ponton (1933), and Hanna (1933), apply the figures of Soper and Obson to the estimation of time of formation of the Florida diatomaceous peat deposits.

Atkins (1933) calculates that in a 10 m. water column in the English Channel, which is probably of sufficient thickness to include the greater portion of the zone of diatom productivity, the maximum thickness of diatom substance traversed is only one-fourth of a millimeter, probably on the average only one-tenth of a millimeter. This, not allowing for a total of several yearly crops of diatoms, or, on the other hand, for re-solution that might occur, agrees favorably with figures for annual increment of diatomaceous sediment arrived at by other means. The second method of measurement mentioned, which consists in submerging some suitable surface for a long interval of time and then measuring the amount of material deposited, has so many difficulties due to disturbance of the material and the very slow rate of accumulation that it may be passed over as having little to offer of quantitative significance.

Attempts have been made to estimate rate of sedimentation from the thickness of accumulated sediments on submarine telegraph cables raised for repair after a submergence for many years, but this has the very serious disadvantages of uncertainty as to how deeply the cable may have sunk in the soft sea-floor sediments when laid, and of how much sediment may have been washed away when it was raised to the surface.

Comparatively little has been done thus far with the third method of determination above mentioned, but the method seems to offer promise under suitable location of proper conditions. The difficulty is to find situations in which tree-ring growth can be confi-

dently compared with a certain definite thickness of sediment without discrepancies due to compaction of sediments. Some suggestive work has been done in correlating prehistoric human artifacts with levels in diatom beds, but has the danger of assigning erroneous levels to simultaneously formed materials through differential settling of the artifacts or the sediments, unless they are so firmly implanted that their true chronology can be ascertained. Correlation of different levels of micro-fossil remains, such as resistant plant pollens from changing land plant floras of determinable periods, with the corresponding diatom sediments at these levels, is most promising in avoiding this discrepancy from differences in compaction of the sediments. This ties certain levels of submerged diatomaceous deposits up with determinable land plant stages, which can be further correlated with other assignable time units. The diatoms may be inversely helpful as chronological indicators in some peat deposits where the pollen remains have been removed by smouldering fires, but the siliceous diatoms standing high temperatures remain (Sears and Couch, 1932). The latter authors estimate deposition of a foot of peat in 300 years, and correlate the sediments with buried cypress stumps of determinable age. Their figures for the deposit they were dealing with are somewhat higher than those earlier mentioned, and it is possible that in this case they were skewed to the higher rate by the inclusion of a high proportion of more rapidly accumulating sub-surface sediments.

Among the work of other authors Dewall (1929) considers rate of diatomaceous sedimentation extensively and methods for determining it, and he felt able to make accurate time determinations for interglacial deposition by actual counts of the strata of diatomaceous sediments at Lüneberg. These were closely correlated with all types of included fossils, and with physical and chemical studies of the deposits. Gams (1927) assigned an age of 13,000 to 16,000 years for the deposits at Lunz, with an estimated rate of deposition of 1 mm. per year, a rather high rate compared with the foregoing. His studies are correlated with Scandinavian chronology and with other fossil remains, and forest succession. Gistl (1928) gives accurate determination of the last interglacial period at Lüneburg as being 11,000 to 12,000 years, compared with an estimate of 8,000 years by Gams, which relatively insignificant difference it would seem might be accounted for by differences in the material examined.

This is no attempt to exhaust the literature as to rate of diatomaceous sedimentation, but gives a representative statement from some of the more comprehensive studies. Although there appears to be a considerable range of discrepancy in the figures of various authors for rate of sedimentation, this is hardly significant, and considering the uncertainty of the premises for measurement, it is noteworthy that they generally fall well within the same relative order of magnitude. Chiefly valuable seems the conclusion that sedimentation occurred at an extremely slow rate, and that probably the lower rates for sediments accumulating in deep waters represent the most conservative view. In the author's somewhat limited experience, the more data there is accumulated, and the more careful the studies of the many variables involved in rate of sedimentation, the less likelihood there seems of arriving at an explicit figure for this rate, or of its having any value for general application, should the particularly favorable conditions in some location permit of an accurate determination. Perhaps we should feel more pleased than we have been disposed to with the seemingly unsatisfactory conclusions so far attained.

COMPARISON OF DEPOSITS

Returning now to consideration of the differences in sediments it may be seen from the foregoing table, that some, like those of Grassy Lake, are four times as thick as others, such as the deposit in Crystal Lake, and represent four times as

fast a rate of accumulation or four times as heavy an annual increment, for their basins were probably formed at approximately the same time and sedimentation has presumably been in progress just about the same length of time in both. But correlations of rate on the basis of equal units of increment are not wholly true, for in Crystal Lake the deposit, lying at a depth of 40 feet of water, is relatively thin, derived from the light deposition of a lake low in nutrients, where the sediments were laid down consistently in deep water, with little change in the slow even rate throughout the history of their accumulation; whereas in Grassy Lake the upper layers show a change in more recent times to faster accumulating, coarse sediments, dominated by the heavily lignified remains of higher aquatic plants, compared to which the rate in the lower layers was relatively less rapid, simulating that of the other deeper water sediments. These represent the extremes both as to amount and rate of accumulation.

Although it is well recognized that lakes tend to change to a higher aquatic flora, with more rapidly accumulating sediments as their beds fill to a shallow depth of water as in Grassy Lake, correlation with depth does not hold as a consistent factor in the composition and rate of formation of diatomaceous sediments. Spring bogs near Jute and St. Germain lakes in Vilas county have highly concentrated diatom sediments of which the surface lies but a foot or less under the water surface. These deposits, which are relatively not very thick and which lie in shallow water, give no indication of irregularity in rate of deposition such as is found in waters of the Grassy Lake type, and have likewise no residue of higher aquatics.

No correlation is practicable between rate of reproduction of diatoms, or total annual production of diatom silica in a lake, and the rate of accumulation of its sediments. There is conflicting evidence as to how much of the fixed silica may be deposited, and what portion may be redissolved. Some workers give experimental evidence of considerable re-solution of diatom shells in the long time it takes for them to settle to the bottom of a body of water. Certainly the prolific, but very lightly silicified, species *Asterionella formosa* and *Fragilaria crotonensis* are not found in fresh water sediments at all in accordance with their great abundance as dominants of the phytoplankton of certain lakes, which, it would seem, must be accounted for by re-solution of their shells. However, in neutral or slightly acid waters, the deposition of diatom silica would seem to be a one-way process, for very delicate though substantially silicified diatom shells reach the bottom sediments and remain there indefinitely with no indication of corrosion or re-solution.

This is a secondary matter, the significant thing being, so far as the building of deposits is concerned, the maximum utilization of available silica in accordance with Liebig's Law, and its maintenance at a constant low level over long periods. The dissolved silica brought into a body of water in excess of this constantly maintained low level represents that which is fixed and deposited.

In interpreting the rate of sedimentation in emerged diatomaceous deposits, with allowances for diatom type, compaction, and proportionate diatom composition at various stages of deposition, a study of the conditions of deposition in present submerged diatomaceous peats is perhaps the best criterion. Such studies indicate the higher percentage of diatomaceous silica (50 to 65%) in the deeper forming sediments, with a lower content relative to ligneous organic matter in the shallower sediments (such as those of Irving and Grassy lakes) in the order of (20 to 40%). The diatom *Melosira granulata* is a typical and frequent representative of the deeper type of sedimentation in fresh waters, while such epiphytic forms as *Cymbella* and *Epithemia* are the frequent dominants of shallower deposition. Thus, from the composition of the diatom flora in a fossilized earth can be

determined the probable depth of water and proportionate diatom content of an earlier sediment, with ideas as to its compaction and rate of accumulation, providing, of course, for possible exceptions when, due to unusual environmental conditions (as in the bogs), other factors may alter the conventional form of deposition. The compactness of the consequent sediments depends closely on the diatom type, and that in turn on the general ecological conditions governing the composition of the diatom flora.

MINERALIZATION OF DIATOMACEOUS SEDIMENTS

Formation of the pure, whitish, diatomaceous earths, exposed in large beds in many parts of New Mexico, California, Nevada, Idaho, Oregon, and other western states, may be thought of as the climax of a process comprising two phases: 1) sedimentation, and 2) fossilization or mineralization, for want of a more specific term.

The concentrated diatom sediments of many of the cold, clear lakes are a fine example of the first step of this process, and it is quite apparent that they are the preliminary stage of the potential dry white diatomites such as above mentioned, which latter represent good examples of the completed process, although it seems apparent that the sediments in the first condition have far to go before reaching the final compacted and purified state. Intermediate steps in this transformation seem conspicuously lacking or unapparent, and it is not clear what physical or chemical processes thick beds of the submerged sediments must undergo to reach the final purified state.

Nor do the terms "fossilization" or "mineralization" truly express the nature of this transformation, resulting in a so-called "non-metallic mineral," although their use seems fitting because they do picture well the mass end effect attained. Specifically they are both ambiguous, because many of the diatom shells in the deeply submerged lake deposits are of sufficient antiquity and state of deposition to have already come into the category of fossils; and they undergo no intrinsic change whatever in the transformation from a flocculent, submerged, organic sediment, to a compact, purified diatomaceous earth, involving some alteration such as is commonly associated with the term mineralization. The term "sub-fossil," not well defined but in good usage in diatom literature, is found convenient in application to diatom sediments in this preliminary or transitory condition.

Although it is not known just what processes effect the thorough oxidation and removal of organic matter and the final high purification of a diatomaceous earth, there is evidence of certain conditions which favor this change, and which may be briefly outlined as follows:—

1. The preliminary accumulation of a proportionately rich diatomaceous "ooze," free of impurities and with little organic matter (the latter being chiefly that of a delicate structure obtaining from the diatoms themselves), produces a gray to sometimes almost whitish material when dry, from which there is comparatively little organic matter remaining to be removed.

2. Alimentation by aquatic animals, decomposition by bacteria, and solution, further diminish the relative organic matter content while in a submerged state.

3. Elevation and exposure of a bed under good drainage conditions tends to promote the leaching, decomposition, and oxidation processes which result in the final slow removal of all organic matter without any harmful effect to the diatom shells themselves. Where good leaching and drainage conditions are not present, decomposition appears to be retarded, and more or less extensive "corrosion" of the diatom shells is apt to occur.

4. Drying, exposure to air, and sunlight, have a minor surface effect in the bleaching of diatomaceous sediments.

As to the proportionate part played by these various factors, or the duration of time necessary to bring about purifica-

tion of a bed of some thickness, it is difficult to say. Suffice it to say, however, that the final removal of all traces of extraneous material from the interior of such a deposit must be a very extenuated process. Leaching, which is certainly one of the important factors and is doubtless greatly facilitated by the natural porosity of diatomaceous earth, sometimes brings in undesirable or foreign materials as well as taking them out, most common of which is iron, often seen as yellowish streaks through the seams of an exposed deposit, especially where drainage is not too perfect.

The foregoing summarizes in a general way what is known, or perhaps of equal importance, what is not known, about the deposition of diatomaceous sediments.

At least, the accumulation of vast beds of such very pure, and of such slowly-forming sediments is a revelation of the fine precision and of the relentless patience of natural processes.

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DOLOMITIC MOTTLING IN THE PLATTEVILLE LIMESTONE

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ABSTRACT

Laboratory study of dolomitic mottling in the lower Platteville limestone of the Minneapolis-St. Paul, Minnesota region shows dolomite distributed through the rock in an anastamosing, irregularly pipe-like manner. Alteration of primary structures and lack of control by jointing indicate that dolomitization occurred after lithification but before jointing. Dolomitization is regarded as effected by introduced magnesian solutions migrating laterally and vertically through permeable zones in the limestone.

STATEMENT OF PROBLEM

In the vicinity of Minneapolis and St. Paul, Minnesota, the lowest member of the Platteville formation is a gray, finely-crystalline, thin-bedded, mottled dolomitic limestone about 11.5 feet thick. Thin, irregular shaly partings occur at intervals of ½ to 8 inches. Fossils are abundant and many occur in lenticular zones parallel to the bedding. The weathered rock, light chalky gray in color, is prominently mottled by small irregular patches of yellowish-brown limonitic stain due mainly to oxidation and hydration of ferrous iron present in the dolomitic parts of the rock.

Limestones, thus mottled by dolomite, are commonly regarded as products of incipient or arrested dolomitization. Many dolomitic limestones are thought to have passed through such a stage in the progress of their formation.

This paper describes the results of a laboratory study of the mottled Platteville limestone undertaken to determine the manner and time of dolomitization. The author is greatly indebted to Professors G. A. Thiel and F. F. Grout of the University of Minnesota, Professor A. H. McNair of Dartmouth College, and especially to Professor J. L. Rich of the University of Cincinnati for much helpful criticism and assistance.

METHODS OF STUDY

Two nearly complete vertical series of samples of the mottled Platteville were taken. One is from the quarry of the Minnesota Crushed Stone company in northern Minneapolis, and the other from a quarry operated by the Public Works Administration at the north end of Mendota Bridge, approximately 9.5 miles south-southeast of the first locality. These localities are shown on the geologic map, figure 1.

For megascopic examination, large specimens of the mottled Platteville were sawed both normal and parallel to the bedding into slabs about ½ inch thick and not over 6 inches square. Cut surfaces were polished and then were etched by immersion for one minute in 1:100 HCl. Etching brought dolomite and shaly partings into positive relief.

Calcite and dolomite were differentiated by selective chemical staining.* The

* Stains with Turnbull's Blue and with silver chromate were used. The stain with Turnbull's Blue is produced by immersing the specimen for one minute in a solution of 0.5 gm. $K_3Fe(CN)_6$ in 250 cc. 1:100 HCl. By reaction of ferrous iron in dolomite with ferricyanide a permanent deep blue stain (ferroferricyanide or Turnbull's Blue) is formed on dolomite. Calcite is not stained. After staining, the slabs are rinsed for about one minute in running water.

With the silver chromate stain described by Krumbein and Pettijohn, calcite is stained a dark reddish brown. Dolomite is not affected. The specimen is immersed for 2 to 5 minutes in a 10% solution of $AgNO_3$. After careful rinsing in distilled water, the specimen is immersed for 1 minute in a 5% solution of K_2CrO_4 and rinsed in running water. Ag_2CO_3 precipitated on calcite is converted, upon contact with K_2CrO_4, into Ag_2CrO_4.

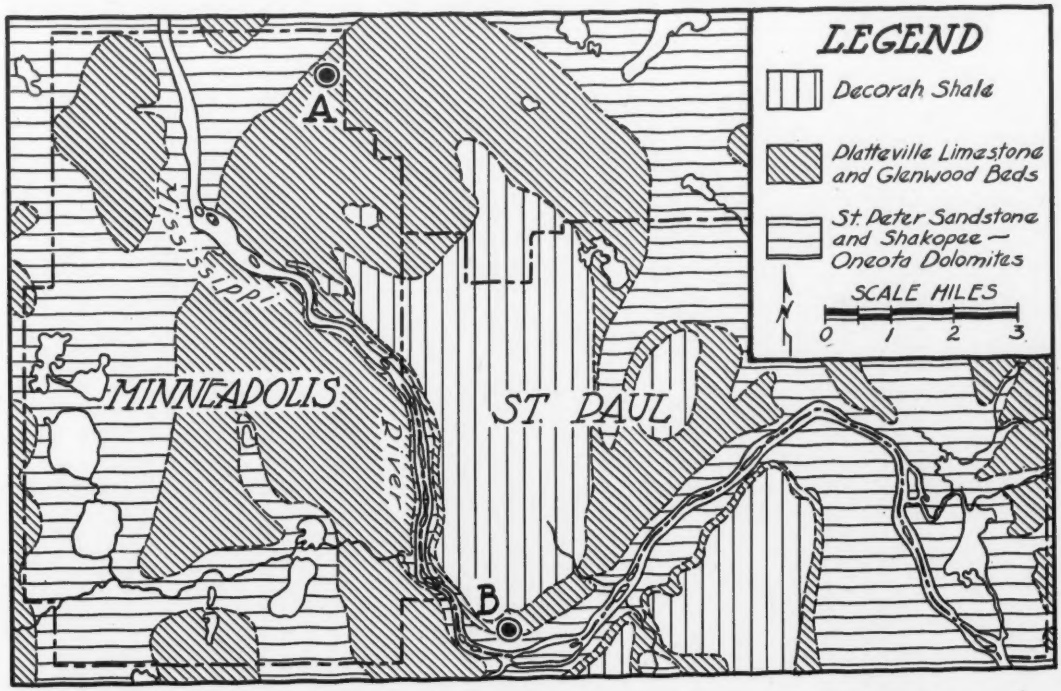


FIG. 1.—Geologic map of part of the Minneapolis-St. Paul Metropolitan district showing sampled localities of the Platteville limestone. Locality A is the Johnson Street quarry of the Minnesota Crushed Stone Company; locality B is the Public Works Administration quarry at the northern end of Mendota Bridge. (After Schwartz)

Turnbull's Blue stain, which colors dolomite but has no effect on calcite, depends upon the presence of iron in dolomite and its absence from calcite. Therefore, the stain may be considered somewhat unreliable because not all dolomite is iron-bearing. Steidtmann, however, has reported consistently good results with this stain. Its effectiveness has been carefully checked by the writer by comparison with other stains.

For mere differentiation of calcite and dolomite, the reddish brown silver chromate stain on calcite is the more reliable since it depends only on certain inherent properties of calcite and dolomite. Its disadvantage in the study of the Platteville limestone is that on stained surfaces both dolomite and the shaly partings appear as light gray areas in positive relief and are difficult to differentiate. Furthermore, the relation of dolomite and partings to textures and structures of the limestone is obscured. Both difficulties were obviated by using the stain with Turnbull's Blue.

Carefully etched and stained slabs of dolomitic limestone were examined with the binocular microscope. Thin sections were stained by both of the techniques described but were not etched. Insoluble residues were secured by digesting the crushed rock in hot 1:10 HCl.

TEXTURES AND STRUCTURES OF THE LIMESTONE

The limestone portion of the mottled Platteville is very fine-grained and is composed of anhedral calcite grains, predominately less than 0.015 mm. in diameter. On polished surface, it shows an obscure mottling due to a slight color difference in small, irregularly shaped adjacent areas. On etched surface, this mottling is seen as a blotchy mixture of fine grained creamy gray limestone and clearer, slightly coarser-grained, more fossiliferous and pyritiferous limestone. In thin section, the mottling is hardly noticeable.

Fossils are small and occur in abundance throughout the limestone, especially in lenticular streaks parallel to the bedding. With them is associated much authigenic, euhedral pyrite.

Shaly partings are considerably less resistant than the limestone layers and on weathered surfaces form longitudinal grooves giving an outcrop a comb-like profile. On sections normal to the bedding, the partings appear as rather irregular wavy laminae commonly less than $\frac{1}{2}$ inch thick. Single partings do not persist laterally for very great distances and even groups of partings do not persist for so great a distance as that between the two localities examined. Insoluble residues of the mottled Platteville are composed very largely of the material of the partings. The percentages of insoluble residues plotted graphically in figure 2 may be taken to indicate roughly the degree of development of the partings. Examination of the percentages for the two sections shows a variation in total amount of about 3 per cent and an almost total lack of detailed correlation in vertical section.

Partings consist principally of waxy chalcedonic silica with which is associated much anhedral pyrite. Rounded, dusty grains of detrital quartz and other minerals of silt and smaller sizes occur sparingly. On etched surfaces the partings show delicate meshwork structures brought out by the solution of included calcite and dolomite. The silica forms external molds of some fossils but has not replaced any of them. From the partings small veinlets of chalcedonic silica project at rather small angles.

Numerous calcite veinlets occur in the limestone. Some of these cut across shaly partings and, more rarely, cut across fossils. The veinlets are usually less than 0.5 mm. in cross section and are rarely more than 2 cm. in length. Most veinlet walls are sharp but some are vague. Calcite of the veinlets is anhedral and most of the grains are about 0.075 mm. in diameter. Small flecks of pyrite occur in the central portion of some veinlets. Locally calcite veinlets are cross-cut by silica veinlets.

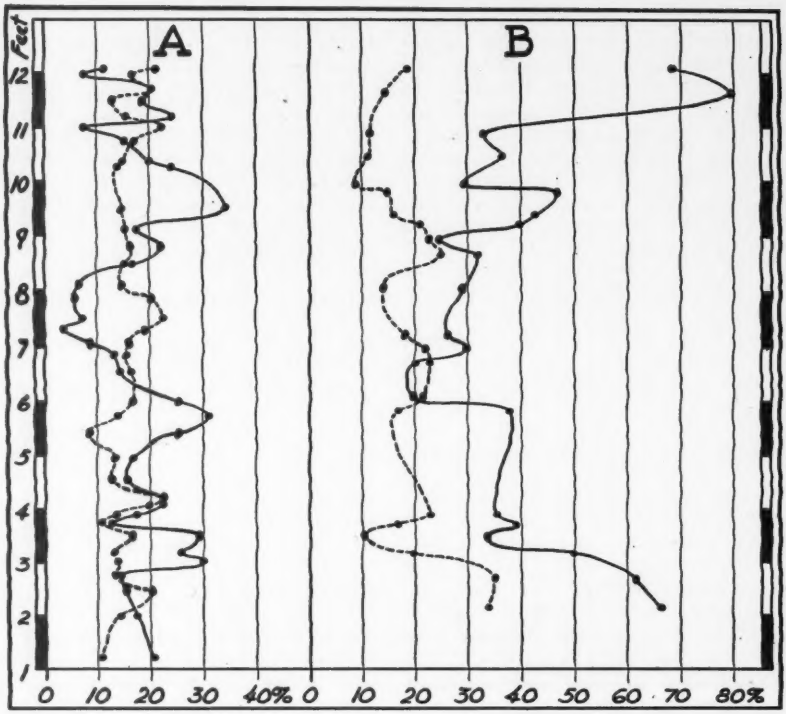


FIG. 2.—Diagram showing variations in percentages of dolomite (solid line) and of insoluble constituents (dashed line) in the mottled Platteville Limestone from the two localities shown in figure 1. Variations are plotted against positions in the section. Locations of samples are marked by dots. The uppermost sample at each locality is at the top of the mottled Platteville.

SUGGESTIONS AS TO ORIGIN OF THE LIMESTONE

Textures and structures of the limestone suggest that it originated as a fossiliferous calcareous ooze. With this was deposited considerable finely divided, probably hydrous, silica forming partings between the calcareous layers. The irregularity of the partings may be accounted for by initial irregularity modified by slight deformation and rearrangement during compaction. Calcite veinlets are interpreted as fractures formed by slumping during accumulation and by weak tensional forces set up during compaction. These are, therefore, regarded as primary structures.

NATURE AND DISTRIBUTION OF DOLOMITE

Megascopically, dolomite patches are extremely irregular in shape and variable in size. Some, up to 7 cm. in length, are elongate parallel to the bedding, but this is not universal. Indeed, others are nearly at right angles. Many are connected by thin stringers and quite commonly irregular patches lie in zones parallel to the bedding, along shaly partings, or as tongue-like extensions from these. A

three dimensional wooden model constructed on the basis of large sections cut ½ inch apart shows that large areas of dolomite form solid structures of very irregular shape extending laterally and vertically throughout the rock. Few patches are truly isolated and these usually are of small size.

The dolomite areas of stained slabs were measured with a polar planimeter and the percentage of dolomite per unit of surface area was calculated. The percentage of dolomite is plotted in figure 2 against position in the section. The percentages of insolubles are similarly plotted. It will be noted that the percentages of dolomite, like those of insolubles, show no consistent vertical variation. There is a tendency, however, for maxima and minima in both sections to occur at corresponding stratigraphic positions. Generally the section from Mendota Bridge (locality B) is the more dolomitic. There seems, however, to be little of value for correlation.

Microscopically, dolomite occurs as euhedral rhombs and anhedral grains ranging in diameter from 0.03 mm. to more than 0.12 mm. Isolated crystals are commonly euhedral, particularly where they occur in a matrix of calcite. In areas that are most dolomitic, anhedral grains are more common. Even in these areas, however, some silica and calcite is interstitial. Isolated crystals usually contain nuclei of calcite. A calcite nucleus may constitute more than 25 per cent of the containing dolomite crystal. In areas of more abundant dolomite, calcite nuclei become fewer and smaller. No zoning was noted.

Patches of dolomite commonly grade outward into calcitic limestone by a progressive decrease in the amount of dolomite present. Locally the transition is more abrupt. Dolomite is not limited in its occurrence to patches or gradational zones, but it is found also as isolated rhombs sparingly disseminated in the limestone.

Although lenticular zones rich in fossils are found to contain small patches of dolomite and are encroached upon or entirely cross-cut by other patches, fossils are few or entirely lacking in the dolomitic areas. Within these areas some fossils are entirely surrounded by dolomite and others contain euhedra which may or may not pierce the outline of the shells. Commonly fossils are absent and little indication of their former presence may be noted.

Within shaly partings, dolomite occurs chiefly as anhedral grains interstitial in chalcedonic silica. In tongue-like extensions of dolomite from the partings, dolomite tends more to be euhedral and the silica between the grains to be dolocastic. Narrow silica veinlets similar to those mentioned previously project from some of these areas. Dolomite is found forming dolomite "veinlets" among many of these.

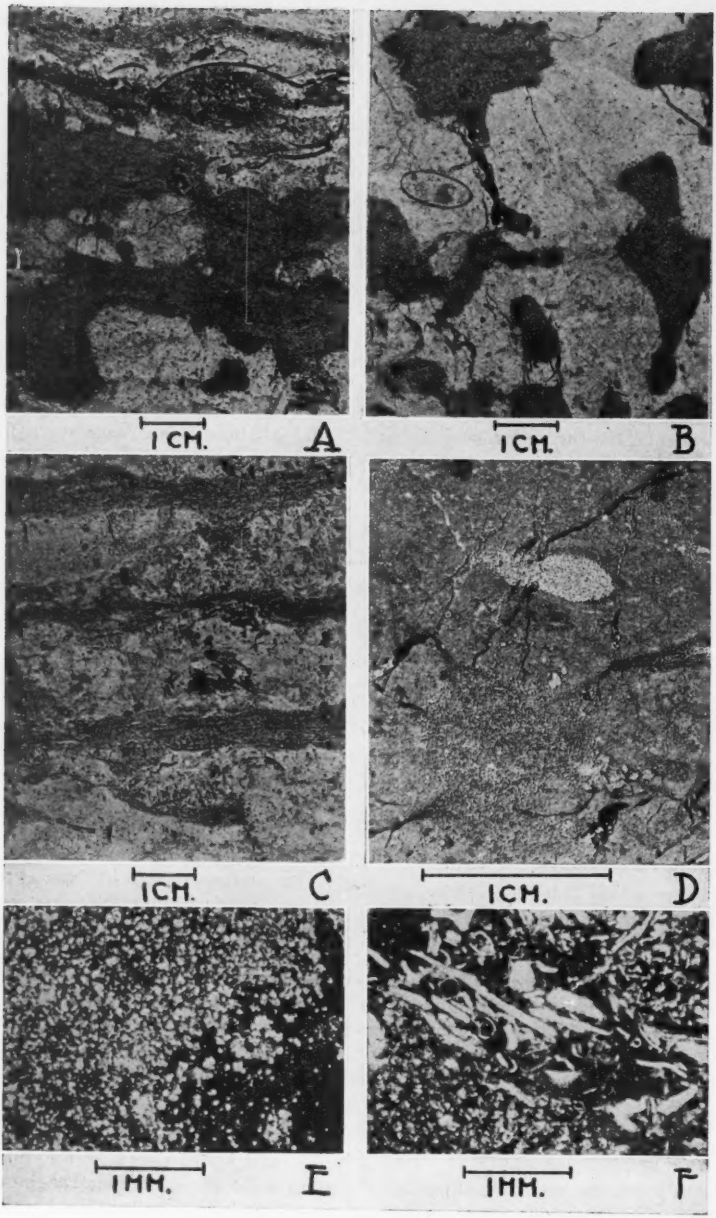
Calcite veinlets in many places pass through shaly partings except where these are dolomitic. Veinlets may project into dolomite areas for short distances, but they commonly end very abruptly at the border. Not one was observed to extend entirely through an area of dolomite. However, dolomite occurs locally along the periphery of calcite veinlets just as along the silica veinlets.

Joints, prominent in the Platteville, may be healed with vein calcite containing considerable pyrite. The joints cross-cut dolomite areas but show no evidence of having controlled or affected their distribution.

INFERENCES AS TO MANNER AND TIME OF DOLOMITIZATION

Rhombs of dolomite sparsely scattered through the limestone may possibly have formed during deposition of the limestone, or they may represent a disseminated replacement. With the possible exception of such disseminated grains, which form a relatively small proportion of dolomite present, dolomite was clearly developed by replacement of calcite.

Fossils are not only less abundant in areas of dolomite than elsewhere but also show stages of replacement ranging from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those where the fossils are composed entirely of calcite to those almost entirely replaced by dolomite. Where dolomitization has been complete the only indication of the former presence of fossils is an occasional rough pyrite mold.

Calcite veinlets are obliterated by dolomite. That the veinlets in some instances project into dolomite areas for short distances indicates that the coarse grained veinlet of calcite was less susceptible to replacement than was the surrounding finer-grained calcite of the limestone. In many places, replacement has followed the periphery of such veinlets (and of silica veinlets) forming the dolomite "veinlets" already mentioned.

In and along shaly partings as well as in those areas more or less isolated from them, dolomite has developed by replacing calcite. Where replacement occurred in the partings, the spaces formerly filled with calcite were generally smaller than the prevailing size of the dolomite grains. Therefore, most dolomite in these areas is anhedral. Euhedral rhombs of dolomite are found most commonly as crystals disseminated in the limestone; in dolomite patches, except where these are developed along shaly partings; and as advance crystals of these areas grading outward into the unaltered limestone. Anhedral grains are found in interstices of shaly partings and in dolomite patches between euhedra of dolomite.

Because dolomite crystals in contact with calcite tend to assume rhombohedral shapes, but are commonly anhedral in contact with other dolomite crystals, some writers have thought that where anhedral grains are found, the rock was sufficiently rigid to prevent the growing crystals from crowding each other aside. In the mottled Platteville, dolomitization is regarded as having taken place by an initial disseminated replacement of calcite by euhedra of dolomite. Continued replacement of calcite between these first-formed euhedra and mutual interference of closely spaced grains caused the development of anhedral grains around and between the euhedra. The observation that euhedral grains are commonly surrounded by anhedral grains is a criterion bearing on the state of the limestone at the time of dolomitization. It is at least suggestive that the limestone was rigid to the extent that the grains, now anhedral, were unable to crowd adjacent grains aside in order to grow to euhedral shapes.

The presence of calcite veinlets indicates that at the time of their formation the limestone was sufficiently rigid to fail by fracturing and to maintain open spaces which were filled with calcite. Re-

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FIG. 3.—A. Platteville limestone cut normal to bedding. Large irregular medium gray areas are dolomite stained with Turnbull's Blue. A single thin shaly parting shows at the top. Below this is a narrow fossiliferous zone. Sections of some of the large fossils are black. Limestone areas are light gray.

B. Platteville limestone cut parallel to bedding and stained with Turnbull's Blue. Irregular gray patches are dolomite. A few fossils and calcite veinlets show in the light gray limestone areas.

C. Platteville limestone cut normal to bedding and stained with Turnbull's Blue. Three shaly partings are very sparingly dolomitized. Sections of fossils are abundant. Note mottling in the light gray limestone portions of the rock.

D. Strongly etched surface of Platteville limestone cut normal to bedding and stained with Turnbull's Blue. Dolomite (light gray areas in positive relief) obliterates several small calcite veinlets (dark gray).

E. Photomicrograph of Platteville limestone. Calcite is stained with silver chromate. Shows strongly dolomitized area (light gray) grading outward into little altered limestone. Note abundance of calcite nuclei in dolomite grains.

F. Photomicrograph of Platteville limestone. Dolomite (stained with Turnbull's Blue) is area of closely packed coarse grains. Shows encroachment of dolomite upon and partial replacement of zone of fossiliferous limestone.

placement necessarily was later than veining.

Available evidence is insufficient to indicate with much certainty the time at which dolomitization occurred. The replacement nature of dolomitization, occurrence of anhedral grains of dolomite between dolomite euhedra, replacement of calcite veinlets, and lack of control by jointing are thought to justify assigning the time of dolomitization to that rather indefinite period between the lithification of the Platteville and its jointing. It is regarded as probable that the process was pre-emergent.

Dolomitization by replacement must have been effected by magnesian solutions. These may have been trapped in the calcareous ooze at the time of its accumulation or may have been introduced later. During lithification of the mottled Platteville, fractures in the rock were healed with calcite. At this time, therefore, solutions connate in the rock or having access to the fractures were of such nature as to deposit calcite rather than to replace it with dolomite. It is not regarded as probable that simple rearrangement of magnesium present in the mottled Platteville (but not as dolomite) could account for the present amounts of dolomite observed. On the other hand, the volume of magnesian water necessary for replacement is larger than is likely to have been connate in the rock. Replacement undoubtedly took place after lithification but the waters trapped in the original ooze evidently were not those responsible for the replacement. This reasoning suggests that magnesium bearing solutions permeated the rock between the time of its lithification and that of the jointing.

It remains to inquire whether the evidence supports the hypothesis of replacement as a result of introduced magnesian solutions. If such solutions were introduced, it is likely that they migrated through the rock along permeable zones. If dolomitization attended migration, the limestone might reasonably be expected, when considered over broad areas or in sections of considerable thickness, to grade laterally or vertically into more completely or less completely dolomitized rock. Furthermore, if the process were arrested before completion, alteration should be most pronounced in and along the channels of migration.

Much dolomite is localized along shaly partings as interstitial grains, as patches, and as tongue-like extensions from partings. These areas, together with those more or less isolated from the partings, are generally connected and form anastamosing pipe-like structures of very irregular shapes extending throughout the rock. Shaly partings at present are more permeable than the limestone layers, and it is not unlikely that this permeability has been but little modified by dolomitization. It is probable that the partings served as the dominant channels through which magnesian solutions migrated. Selective replacemnet of calcite in and adjacent to the partings resulted in a patchy distribution of dolomite. Permeability may have been a dominant factor in localizing replacement which occurred outside the partings. Considerable permeability may have been induced in certain limestone areas by the boring activities of organisms of unknown affinities as has been postulated for certain mottled Ordovician limestones of Manitoba. If so, dolomitization and silicification have been sufficient to effectively mask the organic control.

Although dolomite is developed in and along most, if not all, of the shaly partings, it is a curious fact that dolomite patches are more clearly defined and generally larger and more abundant where partings are thin or few in number or both. Conversely, where partings are thick and numerous, dolomite patches are poorly developed. This relationship is shown in figure 3, A and C. The analyses of insolubles and of dolomite plotted in figure 2 show a tendency for an inverse proportion of these two constituents. In all probability, this relation reflects a

difference in the permeability of the partings. Thick and numerous partings likely would allow more vigorous circulation of magnesian solutions and movement would dominate over replacement. In those areas where partings are thin and few in number, movement of solutions would be slower and the opportunity for replacement greater.

The analyses in figure 2 do not indicate a consistent vertical variation in percentages of dolomite for either section. This evidence is merely suggestive that vertical movement of solutions was not a very important factor in the replacement of the limestone. It is not conclusive evidence as the sections are of too small vertical extent. The analyses, however, suggest a southward increase in the proportion of dolomite in the mottled Platteville. Additional sections must be considered before the suggestion has meaning.

Whereas the time and manner of dolomitization of the mottled Platteville are considered to have been established satisfactorily, the sources of the dolomitizing solutions remain a perplexing problem. Possible sources include solutions of magmatic origin and natural brines trapped in the sediments during their accumulation. The writer is inclined to favor a hypothesis that waters of sedimentation have played a dominant role in dolomitization. The following brief discussion is presented in hope that further investigation of the problem will be stimulated.

If it is postulated that connate solutions were responsible for dolomitization, it is probably necessary for these solutions to have been made more magnesian than they were originally and for them to have moved through the mottled Platteville so that the limestone was exposed to more of such solutions than were originally present. An increase in magnesium content might result from addition of that material to the brines from the skeletons of organisms. Appreciable quantitites of magnesium might also have been derived from calcite as this mineral is known to contain small percentages of magnesium and other elements in place of calcium. In conversation with the writer, John L. Rich has suggested that natural brines connate in the Platteville or in associated formations may have been concentrated in the manner described by Mills and Wells: as a result of evaporation into gases generated in or passing through the sediments. Such relatively concentrated brines may have been moved through the sediments by action of gases or may have been expelled from them because of decrease of porosity attending compaction. Movement of brines probably would have been up the dip along bedding and even vertically where permeability conditions were suitable. Dolomitization may well have attended their migration.

CONCLUSIONS

Dolomitic mottling in the lower member of the Platteville formation is thought to be the result of selective replacement of the limestone. Alteration of primary structures, such as calcite veinlets, and lack of control by jointing suggest that replacement occurred after lithification but before jointing. It is believed that dolomitization attended the migration of magnesian solutions through the limestone along permeable zones, mainly shaly partings. Analyses suggest a southward increase in dolomitization indicating the possibility that the solutions moved northward. The source of such solutions is problematical. An hypothesis considered with favor is that the solutions responsible for dolomitization were natural brines made relatively concentrated by evaporation of water into gases and caused to migrate through the mottled Platteville by expulsion during compaction of the Platteville and associated formations.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 2, PP. 77–84,
FIGS. 1–3, TABLES 1–2, AUGUST, 1942

SEDIMENTARY PETROLOGIC PROVINCES OF THE NORTHERN GULF OF MEXICO

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ABSTRACT

Sediment samples from the northern border of the Gulf of Mexico show regional differences in mineral composition which permit the distinction of four areas of sediments, each with a characteristic mineral suite. These "sedimentary petrologic provinces" are here termed the Eastern Gulf Province, the Mississippi River Province, the Western Gulf Province, and the Rio Grande Province. The mineral assemblage characteristic of each province is briefly described.

ACKNOWLEDGMENTS

The writer wishes to thank Dr. R. Dana Russell, Associate Professor of Mineralogy at Louisiana State University, for his guidance and aid in this study. He is also indebted to Mr. Harold Bissell and student workers in the Sedimentation Laboratory for their assistance in the preparation of the samples, and to Mr. Lyman F. Rhodes IV, Mr. Julian N. Goldberg, and Mr. G. O. Coignet, who aided with the cartography. The M.S. thesis of Robert Bailey, *Recent Marine Sediments off the Texas Coast*, with his slides and samples, was available to the author and was quite helpful. Dr. William M. Cogen of the Shell Oil Company supplied a number of mineral analyses. Dr. Fred M. Bullard, of the University of Texas, kindly furnished the writer a copy of his paper, *Source of Beach Sands on Gulf Coast of Texas*, in advance of publication. In figure one the samples analyzed by Bailey, Cogen, and Bullard are distinguished from those analyzed by the writer.

INTRODUCTION

The average daily contribution of the Mississippi River to the Gulf of Mexico is at least two million tons of sediment (R. J. Russell, 1936; R. D. Russell, 1939). This tremendous volume of detrital material has been spread over a considerable area by wave and current action and by the shifting of active distributaries of the river.

In an attempt to delimit the distribution of this material, sediment samples collected from the off-shore portion of the delta and adjacent areas along the Gulf Coast from west Florida to southwest Texas were analyzed for mineral composition. This study not only indicated the approximate distribution of Mississippi River material, but also demonstrated the existence of four areas in which the sediments possess distinctive and characteristic mineral assemblages. Though the number of samples analyzed is not sufficient to locate accurately the boundaries between these areas, the approximate positions of the boundary lines have been established.

Samples studied were collected by the United States Bureau of Fisheries, the United States Coast and Geodetic Survey, and by Dr. R. Dana Russell in cooperation with these agencies. Standard types of bottom-sampling apparatus were used. Samples selected for mineral analysis are shown in figures 1 and 2. Complete mechanical analyses of these samples were made in the Sedimentation Laboratory at Louisiana State University. The sand separates were then split with a micro-split (Otto, 1933) and bromoformed. After removing the strongly magnetic minerals, each heavy separate was

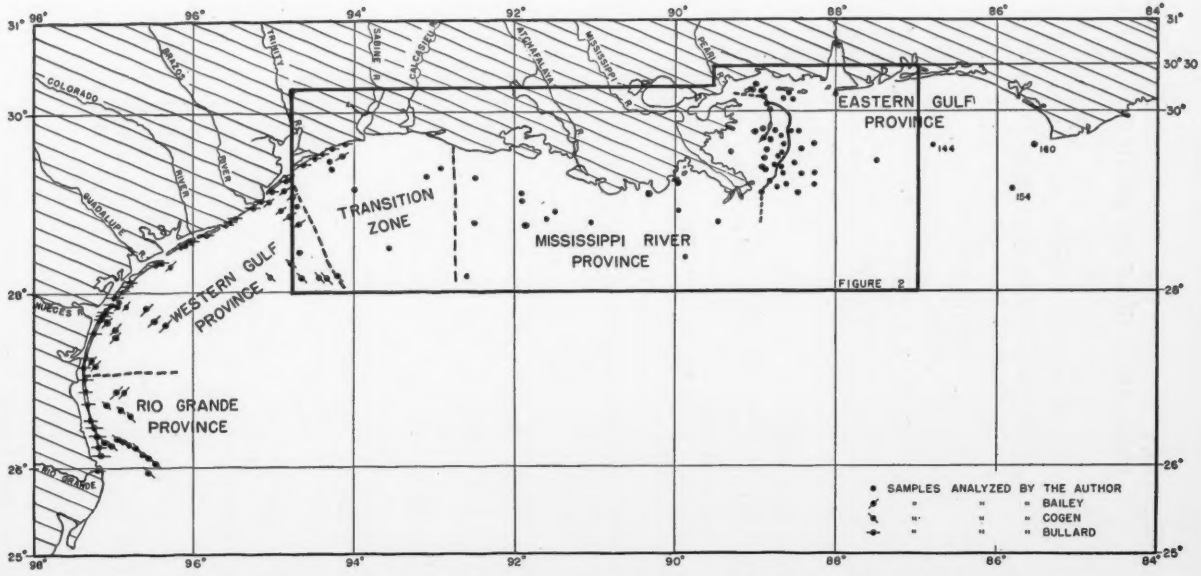


FIG. 1.—Map of the northern portion of the Gulf of Mexico, showing samples analyzed by the writer and others. The location of figure 2 is shown by a heavy line.

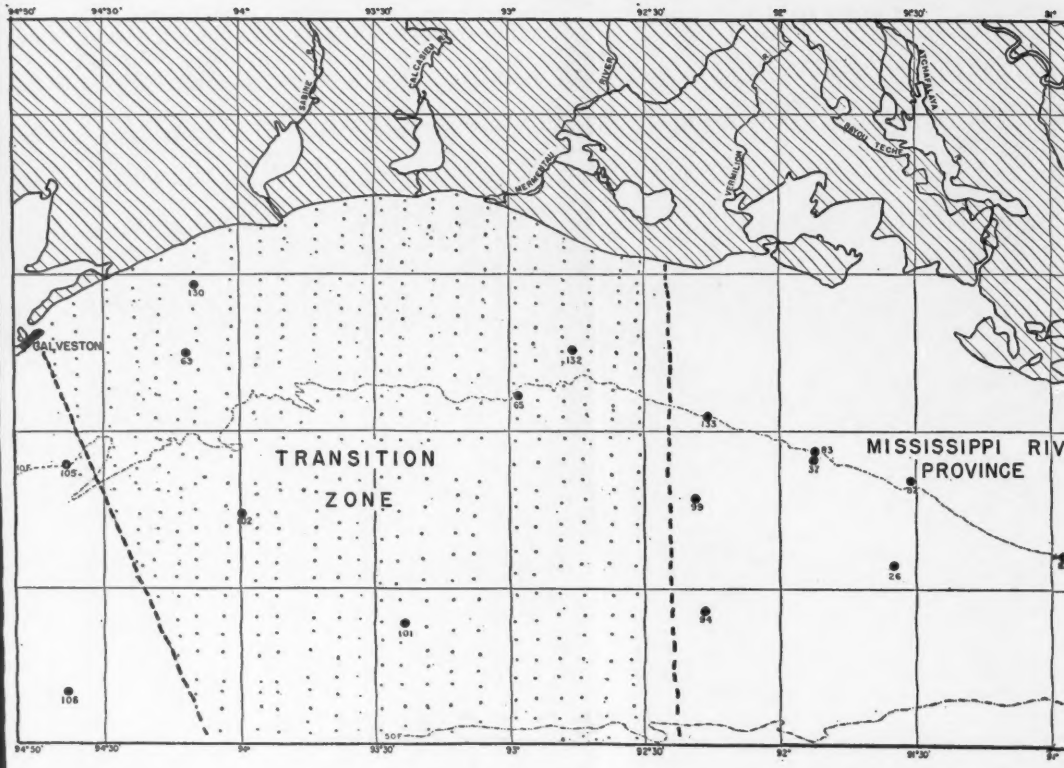
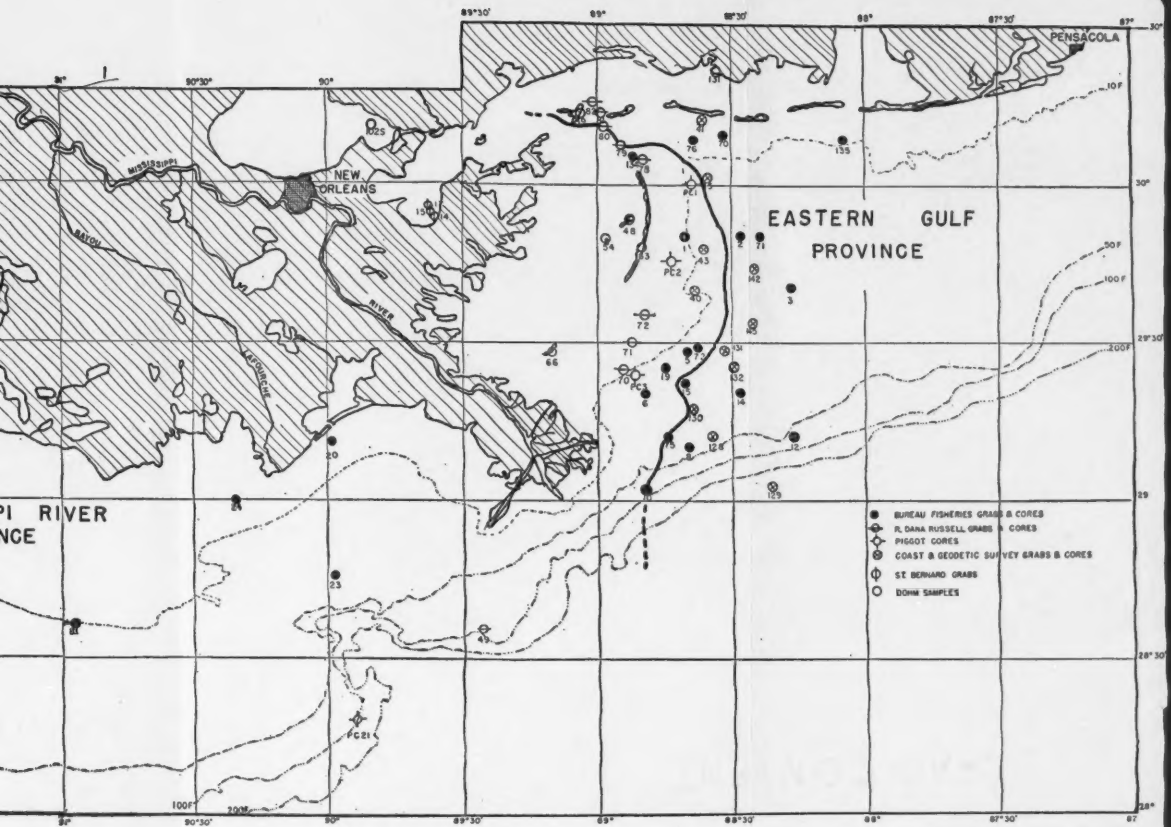
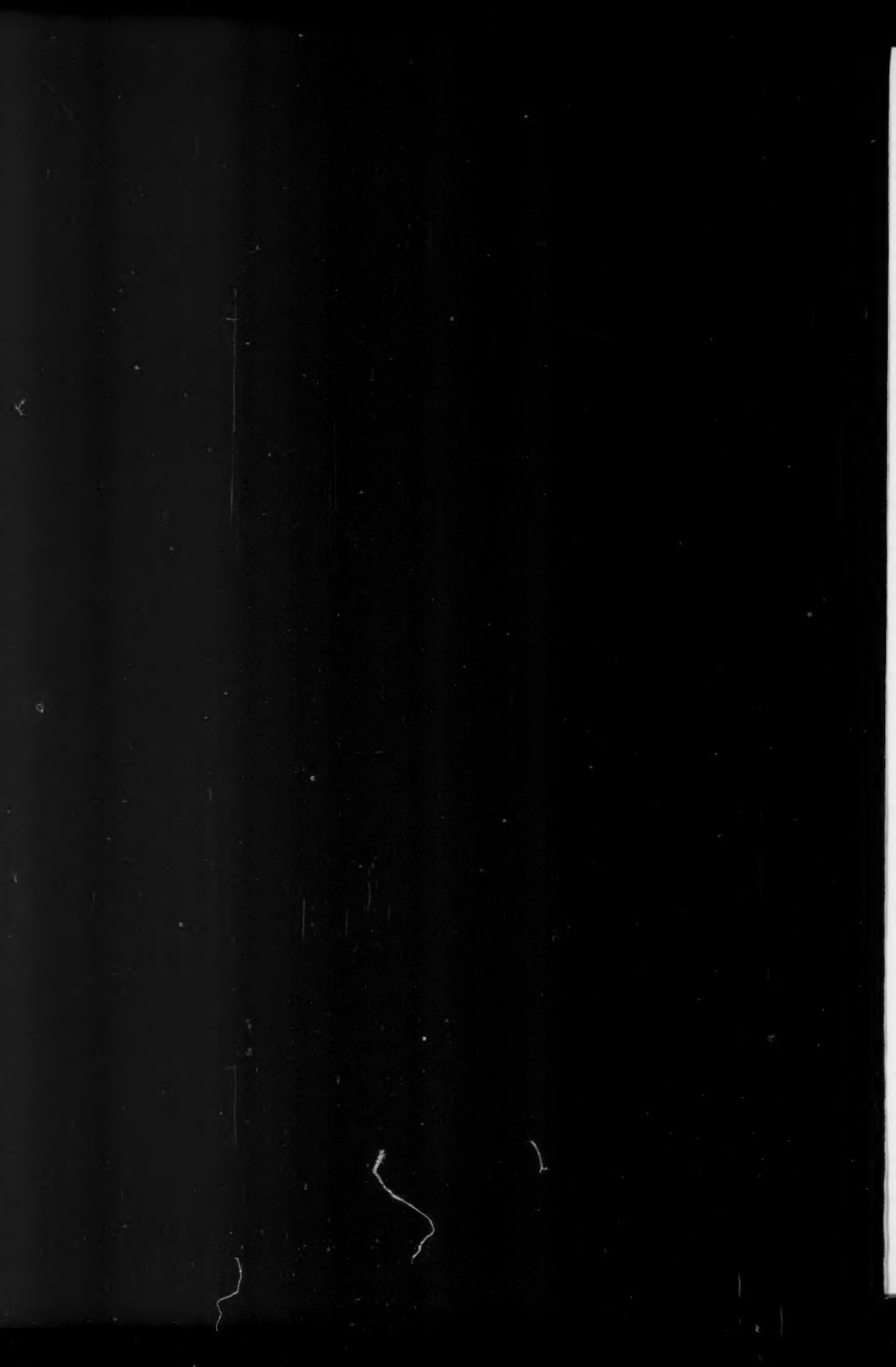


FIG. 2.—Map showing location, locality number, and collec



and collecting agency for samples analyzed by the writer and C. F. Dohm.



mounted in Aroclor 4465[1] and the minerals determined with a petrographic microscope. At least 300 grains were counted on each slide to determine mineral percentages.

The samples show considerable variation in mineral composition. Major differences in composition were found to be geographical and result chiefly from differences in source rocks. These differences form the basis for the separation of the sediments into distinctive areas or sedimentary petrologic provinces. Within each province, the sediments show variations in the percentages of minerals, resulting from differences in sorting. Some of these variations are quite marked, but they did not seriously interfere with the separation of the samples into distinct geographic groups.

It should also be noted that the averages of the samples in the two transition zones, as shown in figure 3 and table 2, do not represent a true average of the mineral composition of sediments in these zones. These samples were chosen to delimit the province boundaries, rather than to afford an average of the mineral composition and frequencies in the transition zones.

SEDIMENTARY PETROLOGIC PROVINCES

Doeglas (1940) defines a sedimentary petrologic province as a "complex of sediments which by their geographical distribution, age and origin form a natural unit," and refers the origin of the term to Baturin (1931). The writer's study distinguishes three sedimentary petrologic provinces along the northern border of the Gulf of Mexico. No samples were available from the Rio Grande area in southwest Texas, but the work of Bullard (1942) and Cogen (1941) establishes a fourth province in that area. For these provinces the writer proposes the names Eastern Gulf Province, Mississippi River Province, Western Gulf Province, and Rio Grande Province (fig. 1).

The heavy mineral suites characteristic of these four sedimentary petrologic provinces are easily distinguished (fig. 3). The differences between the dominantly igneous assemblage of the Mississippi River Province and the dominantly metamorphic assemblage of the Eastern Gulf Province is evident at a glance; the sediments of the Western Gulf Province are similar in mineralogy to those of the Mississippi River Province but have a higher content of leucoxene and a much lower percentage of pyroxenes; the sediments of the Rio Grande Province are easily distinguished from those of the Western Gulf Province by a high content of pyroxenes and basaltic hornblende (see table 2).

The areal extent of the provinces is shown on figure 1. The Eastern Gulf Province extends from a line near longitude 88° 45′ eastward to at least longitude 86°. Only two samples were available east of longitude 86°, so the eastern boundary of this province is not known, but Tyler (1934) has shown that the beach sands of the Florida and North Carolina coasts have a suite of minerals similar to that of the Eastern Gulf Province.

A rather narrow transition zone of mixed sediments separates the Eastern Gulf and Mississippi River Provinces. The western edge of this zone is shown on figures 1 and 2 by a heavy line. Three Piggot cores from two to seven feet in length collected near this boundary were studied to determine the possibility of interfingering of provinces, but analyses made at intervals show no interfingering within this rather short vertical distance.

A broad zone of mixed sediments separates the Mississippi River and Western Gulf Provinces. This zone extends approximately from longitude 92° 30′ to longitude 94° 40′ (fig. 2).

The Western Gulf Province extends southwest to latitude 27° where it merges with the Rio Grande Province. The southern limit of the Rio Grande Province has not been determined.

CHARACTERISTICS OF THE PROVINCES

Eastern Gulf Province.—Samples BF 3 through RDR 81 in table 1 (see fig. 2 for

[1] Aroclor 4465—an artificial resin with a refractive index of about 1.656.

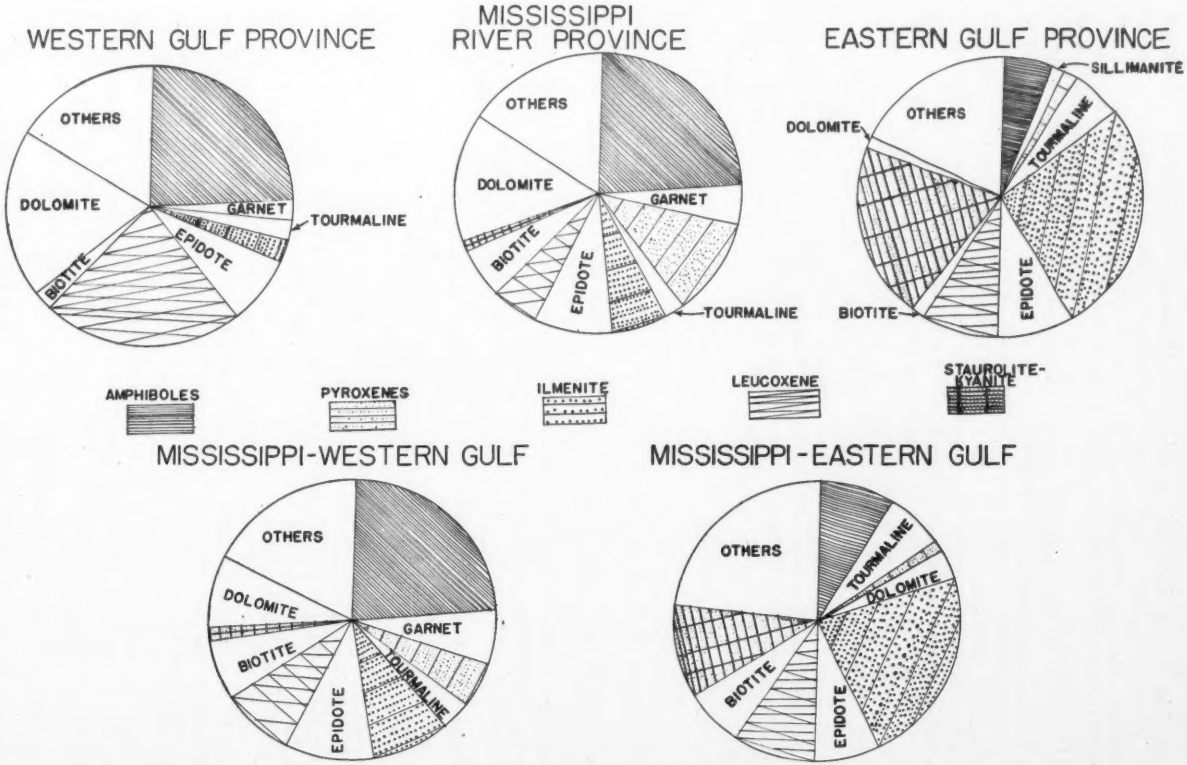


FIG. 3.—Pie diagrams illustrating the average heavy mineral composition of sediments from the three northern provinces and the transition zones separating them.

location of samples) are characteristic of the Eastern Gulf Province; the average mineral composition of these samples is shown diagrammatically in figure 3. Samples BF 2 through RDR 82 are mixed sediments from the transition between the Eastern Gulf and Mississippi River Provinces.

TABLE 2. *Diagnostic Mineral Percentages and Ratios*

Mineral	E. Gulf Province		E. Gulf-Miss. R. Provinces		Miss. R. Province		Miss. R.-W. Gulf Provinces		W. Gulf Province	
	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
Amphiboles	5.5	0.9 to 18.9	8.4	3.7 to 15.1	23.7	15.6 to 36.3	23.8	11.5 to 35.7	23.9	6.7 to 43.9
Pyroxenes	1.4	none to 4.6	1.2	none to 1.5	11.3	5.3 to 18.0	5.0	2.1 to 8.9	0.7	none to 3.4
Kyanite & Staurolite	20.2	8.7 to 38.1	10.6	5.1 to 14.5	1.1	0.03 to 3.8	1.5	none to 4.1	—	—
Ilmenite	27.0	17.7 to 44.0	22.8	13.8 to 31.6	6.2	1.8 to 10.2	8.6	2.5 to 17.8	2.6	0.3 to 8.3
Leucoxene	8.5	5.2 to 11.6	9.1	3.4 to 13.2	5.2	1.0 to 7.9	8.2	4.9 to 12.1	22.8	6.7 to 41.4
Amph./Pyrox. Ratio	3.9		7.1		1.9		4.1		36.1	
Ilmen./Leucox. Ratio	3.2		2.5		1.23		1.17		0.12	

The Eastern Gulf Province contains a metamorphic assemblage which is derived largely from the Southern Appalachian region, either directly from the metamorphic rocks of the bed-rock complex or from surficial deposits of Pleistocene (?) age; reworked Tertiary sands, shales, and limestones probably furnish only minor amounts of material.

A relatively high content of ilmenite, staurolite, kyanite, zircon, tourmaline, and sillimanite characterizes the sediments of this province. The percentages of magnetite, amphiboles, and pyroxenes are all low, probable owing to the character of the source rocks rather than to the instability of these minerals under processes of weathering. This is indicated by the character of the grains, which are fresh and angular, and by the scarcity of secondary minerals. Only small quantities of leucoxene and hematite are present and other alteration products are rare.

Mississippi River Province.—The mineralogy of this province is shown by samples PC 1–1 through RDR 78 in table 1 (also see fig. 3). Samples BF 63 through BF 132 are characteristic of the transition zone between the Western Gulf and Mississippi River Provinces.

The more common heavy minerals (in order of abundance) are amphiboles, dolomite, pyroxenes, epidote, ilmenite, and biotite. The assemblage of this

province is essentially that carried by the Mississippi River today, and has been fully described by R. Dana Russell (1937).

Sediments of the mixed zone separating the Mississippi River and Western Gulf Provinces show mineral percentages intermediate between those of the Mississippi River and Western Gulf sediments.

Western Gulf Province.—This province was established largely on the basis of 22 samples analyzed and described by Bailey (1940). These samples are not shown in table 1, which lists only those analyzed by the writer. The writer, however, had access to Bailey's thesis, slides, and original samples and so assumes responsibility for the conclusions derived from a study of these analyses. William M. Cogen also furnished a number of analyses which aided in delimiting this province.

The mineral assemblage of this province is similar to that of the Mississippi River Province (see fig. 3), though pyroxenes and ilmenite are less common and leucoxene is abundant. This similarity made differentiation of the Western Gulf sediments difficult, especially since there are no distinctive mineral species. Mineral percentages, however, are different from those of the Mississippi River Province, and two mineral ratios were quite distinctive. These are the ratios of ilmenite to leucoxene and of amphiboles to pyroxenes (see table 2).

Many differences in appearance and composition between the sediments of the Mississippi River and Western Gulf Provinces can be explained on the basis of second-cycle sediments and the disappearance of the less resistant minerals by intrastratal alteration and solution. Pettijohn (1941), in a statistical study of the literature, has shown that intrastratal alteration and solution is the dominant factor in the disappearance of "unstable" minerals and results in decreasing complexity of sediments with increasing age. The mineral grains of this province are commonly rounded to subrounded and badly altered. This suggests a considerable period of wear and alteration. Leucoxene weathers from ilmenite; the samples from the Western Gulf Province are low in ilmenite and high in leucoxene. Pyroxenes are less resistant than amphiboles; the sediments of the Western Gulf Province are high in amphiboles and very low in pyroxenes.

Although the Mississippi River at this time seems to be contributing little to the area included in the Western Gulf Province, it appears possible that the mineral assemblage of this province is partly derived from materials laid down by the ancestral Mississippi River and that it represents a concentration of the more resistant elements of these deposits. However, the Colorado, Sabine, Brazos, and other rivers have been and are now contributing sediments to this area and these sediments may account for the mineral assemblage of the province. The Colorado River is known to contribute considerable quantities of hornblende (Bullard, 1942). More detailed information on the mineralogy of sediments contributed by streams to this province is needed before the source areas can be definitely determined.

Rio Grande Province.—Bullard (1942) states that sediments of the Rio Grande Province have an assemblage of heavy minerals, excluding opaques, "containing 60 per cent basaltic hornblende and pyroxene, 10 per cent green hornblende, and only 30 per cent of the more stable minerals such as garnet, rutile, staurolite, tourmaline, and zircon." Analyses by Cogen (1941) confirm Bullard's results. This assemblage is quite distinct from that of the adjacent Western Gulf Province, which is low both in pyroxenes and basaltic hornblende. The sediments of the Rio Grande Province are essentially those carried by the Rio Grande River today. The analyses of Bullard and Cogen indicate that the northern boundary of this province is approximately latitude 27°.

DISTRIBUTION OF SEDIMENT IN THE NORTHERN GULF OF MEXICO

In considering the factors which determine the distribution of sediment in the northern Gulf of Mexico, one should remember that any current of relatively constant direction, no matter how small its velocity, is capable of transporting particles of sand size and smaller in the zone of active wave action. Wave turbulence lifts sedimentary particles above the bottom where even very weak currents may carry them along. Marine currents are, therefore, the principal agents of transportation in the Gulf, as in other large bodies of water (Fleming and Revelle, 1940; Grant and Shepard, 1939; Penck, 1894; Vervey, 1890).

Unfortunately, data on currents in the Gulf of Mexico are rather meager and are limited to those near the surface. No data are available on bottom currents. In the northern and northwestern portion of the Gulf, however, the *Pilot Chart of the Central American Waters*, published by the Hydrographic Office of the United States Coast and Geodetic Survey, shows a persistent current moving east to west, relatively close to shore, with a velocity of .5 to .8 knots per hour. This current (labelled counter-current on the Pilot Chart) moves up the West Coast of Florida, along the Alabama and Mississippi coasts, swings south around the active delta of the Mississippi, and then southwestward along the Texas coast. It appears to be the chief means of distribution of sediment in this area.

Considerable disagreement exists concerning currents in the western portion of the Gulf. Jenkins (1921) states that "in the older English charts a branch of the Caribbean current is shown running clockwise round the Gulf of Mexico through the Gulf of Campeachy past Vera Cruz and Tampico. As a matter of fact, west of the Mississippi delta, the current runs in exactly the opposite direction, and is, in fact, the deltaic water deflected to the west by the rotation of the earth. The surface temperatures prove conclusively that there is no marked influx of the Caribbean current into the Gulf." Later work by the Yale Oceanographic Expedition confirms Jenkins' statement (Parr, 1935).

The Gulf Coast Edition (1936) of the United States Coast Pilot states that "the currents in the western end of the Gulf, from Vera Cruz to Galveston, are weak and uncertain. The currents in the deeper portions of the Gulf are due largely to prevailing winds." Though eastward moving currents are shown on the Pilot Chart, they are seasonal and commonly outside the one hundred fathom line, beyond the zone of vigorous wave action. They do not appear to be capable, therefore, of transporting any large quantity of sediment. The current closest to shore is from east to west throughout the year; this is the only persistent current shown. It is possible that these opposing currents in the Western Gulf, together with storms from the southwest, account for the occurrence of sediments of Rio Grande source as much as 80 miles north of the mouth of that river and also aid in the formation of the mixed zone between the Mississippi River and Western Gulf provinces. The occurrence of this 100 mile wide mixed zone presents an interesting problem. Though not enough samples were available to delimit this zone accurately, those available seem to indicate a gradual transition between the two provinces. In addition to storms and currents from the southwest, possible causes of this wide transition zone are:

1. Dilution of Mississippi River material by contributions from the Sabine, Calcasieu, and other rivers in this area. The mineral assemblages of these streams would exert appreciable influence on the mineralogy of the current-borne sediments.

2. Reworking of sediments previously deposited upon the continental shelf. Recent sediment of the Mississippi River might never be carried far to the west, but exchanged for previously deposited shelf materials, probably late Pleisto-

cene. During the Pleistocene tremendous quantities of sediment were deposited upon the continental shelf. During glacial periods there was considerable erosion and deposition of coarse material farther out into the Gulf than today (Fisk, 1939). Some evidence that the continental shelf may have developed chiefly during the late Pleistocene is furnished by the fact that present day streams, with the exception of the Mississippi, are contributing little sediment to the Gulf. This is well shown in the Eastern Gulf Province. At present the shelf in this area is receiving only small contributions from streams, yet it maintains its uniformity for many miles away from shore, beyond the narrow strip now actively undergoing sedimentation.

In summation, it would seem that sediment from the present Mississippi River is being swept slowly but surely to the west, diluted by the contributions of streams along the coast, perhaps mixed with sediment carried from the southwest by storms or currents, and exchanging with and being contaminated by reworked Pleistocene sediments upon the continental shelf.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 2, PP. 85–89,
TABLES 1–3, AUGUST, 1942

GRAVITY VERSUS CENTRIFUGE SEPARATION OF HEAVY MINERALS FROM SAND

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ABSTRACT

The relative efficiency of gravity and centrifuge separation of heavy minerals in sand was tested. The percentages of heavies by weight differ significantly; the number frequencies do not. Gravity separation tends to effect a cleaner separation of high than of low specific gravity minerals. Centrifuge separation is equally effective for all minerals.

In an extensive study of heavy minerals in the Rio Grande and its Middle Valley tributaries, samples were collected at the same localities at different seasons for several years. The heavy minerals in samples collected in 1937, 1940, and 1941 were separated by gravity settling; those collected in 1938 and 1939 by centrifuge. As an aid to correlation of the results, a study was made to compare the effectiveness of gravity settling and centrifuge separation. It was found that the percentages of heavies by weight obtained by the two methods differ significantly; the frequencies by number do not. A brief presentation and discussion of the data seems appropriate.

For the comparative study, a composite was made from proportionate splits of six individual samples collected in 1938 from deposits in the Rio Grande channel near Albuquerque, N. M. Eight test samples were split from the composite and separately sieved. The .124-.088 mm. size grade of each test sample was split into two approximately equal parts. One part was centrifuged in a Bertholf centrifuge tube (Bertholf, 1940) for five minutes at about 1800 RPM. The other part was placed in a simple filtering funnel, fitted with a rubber tubing and pinchcock, and stirred at intervals for about two hours. The heavy liquid used was acetylene tetrabromide. After the heavies were washed with alcohol, dried, and weighed, the magnetite was removed with a weak horseshoe magnet and weighed. The analytical results are presented in table 1.

Because parts of the same composite sample were used for all laboratory work, the results are affected only by the inherent errors due to reduction in size of the laboratory sample, and by the nonrandom errors of splitting, sieving, heavy mineral separation, and weighing. All of these errors are present in both the centrifuge and gravity settling data, and they should be of the same magnitude in both, except for differences due to the method of separation. Consequently, differences in the magnitude or scattering of data obtained by the two separation methods are a measure of their relative effectiveness.

As shown in table 1, the average per cent by weight of all heavies, of magnetite, and of heavies other than magnetite, is greater for the centrifuged fractions. A test of the means for statistical significance (Croxton and Cowden, 1940) indicated that the difference in amount of magnetite could have been caused by chance errors of sampling, but those for all heavies and for heavies other than magnetite could not.

To check this conclusion, the light separates of four test samples were recentrifuged and the additional crops of heavies thus obtained were washed, dried, and weighed. As shown in table 2, these additional heavies, when added to the original heavy separates, eliminate essentially all weight differences in results obtained by

TABLE 1.—*Data obtained by centrifuge and gravity separation of heavy minerals from the .124–.088 mm. size grade of eight test samples split from a single composite.*

Sample	Weight of .124–.088 mm. separate Grams	Weight of splits of separate		Weight of all heavies				Weight of magnetite				Weight of heavies other than magnetite			
		Centrifuge	Gravity	Centrifuge		Gravity		Centrifuge		Gravity		Centrifuge		Gravity	
		Grams	Grams	Grams	Per cent	Grams	Per cent	Grams	Per cent	Grams	Per cent	Grams	Per cent	Grams	Per cent
1	11.336	5.548	5.788	0.204	3.68	0.189	3.26	0.052	0.94	0.050	0.86	0.152	2.74	0.139	2.40
2	11.116	5.288	5.828	.197	3.72	.212	3.64	.056	.98	.056	.96	.145	2.74	.156	2.68
3	10.120	5.308	5.711	.203	3.82	.203	3.55	.050	.94	.053	.93	.153	2.88	.150	2.62
4	10.775	5.233	5.542	.201	3.84	.200	3.61	.051	.97	.055	.99	.150	2.87	.145	2.62
5	10.760	5.356	5.424	.206	3.84	.192	3.54	.055	1.03	.051	.94	.151	2.81	.141	2.60
6	11.259	5.148	6.111	.195	3.79	.206	3.37	.046	.89	.054	.88	.149	2.90	.152	2.49
7	11.689	5.489	6.200	.182	3.32	.213	3.44	.050	.91	.055	.89	.132	2.41	.158	2.55
8	11.556	5.533	6.022	.199	3.60	.204	3.39	.047	.85	.052	.86	.152	2.75	.152	2.53
Mean	—	—	—	—	3.70	—	3.48	—	.94	—	.91	—	2.76	—	2.56
Standard error[1]	—	—	—	—	4.7	—	3.5	—	5.9	—	5.3	—	5.6	—	3.4

[1] The equation for standard error of the mean of small samples was used.

the two methods of separation. This confirms the assumption that the two splits of each test sample contained essentially equal amounts of heavies. Therefore, the significant difference in weight of heavies obtained by the two methods can only be due to difference in method of separation.

Tyler and Marsden (1937) also reached the conclusion that centrifuge separation yields a greater weight of heavies than gravity separation. For the crushed igneous rocks used in the Tyler and Marsden experiment, gravity settling yielded only 34–73 per cent as many heavies as centrifuge separation. In the present test, the relative efficiency of gravity settling was much higher, ranging from 88 to 104 per cent and averaging 94 per cent.

In contrast to the difference in total weight of heavies obtained by gravity and centrifuge separation, the standard errors about the means of the gravity and centrifuge separates are both small.[1] This shows that equally consistent results may be obtained by either method. Consequently, the weights of heavies in samples separated by gravity settling may be compared with one another as confidently as the weights of heavies of centrifuged samples may be compared.

Each centrifuge, gravity, and "gravity followed by centrifuge" heavy mineral separate was then split to convenient size in an Otto microsplit, and the mineral frequencies by number determined by identifying 325–380 randomly selected grains of each separate. Representative results of these frequency counts, together with averages for all eight gravity and centrifuge samples and all four "gravity followed by centrifuge" samples are presented in table 3. Differences of several per cent commonly occur between the frequencies in the gravity and centrifuge samples. Chi-square tests show that the differences in number frequency, for eleven selected minerals that range in specific gravity from 3.1 to 4.7, are not significant[2] for seven of the eight pairs of test samples or for the averages of the eight samples together.

TABLE 2. *Data obtained by recentrifuging the light fractions of gravity and centrifuge samples of table 1*

Sample	Centrifuge				Gravity			
	Original weight of heavies Grams	Heavies from re-centrifuged lights Grams	Total heavies		Original weight of heavies Grams	Heavies from re-centrifuged lights Grams	Total heavies	
			Grams	Per cent			Grams	Per cent
1	0.204	0.001	0.205	3.70	0.189	0.024	0.213	3.68
3	.203	.001	.204	3.84	.203	.010	.213	3.74
5	.206	.001	.207	3.86	.192	.008	.200	3.78
7	.182	.007	.189	3.44	.213	.005	.218	3.52

[1] As shown in table 1, the standard error about the mean of the centrifuge separates is the larger. Test sample 7, however, appears to have fewer heavies than the other test samples—perhaps because of a splitting error. If this sample is eliminated from both gravity and centrifuge calculations, the standard error about the mean of the centrifuge samples is the smaller.

[2] The chi-square test assumes that samples derived from an infinitely large population. Because the composite from which all test samples were split contained only 3,000,000 or so heavy mineral grains (and consequently was not infinitely large), the assumption is not strictly fulfilled. The error, however, is not sufficiently large to change the results materially.

In contrast, the frequencies by number in the four "gravity followed by centrifuge" separates differ significantly from those in the centrifuge and gravity separates. The recentrifuged heavies are deficient in such high specific gravity minerals as ilmenite (and magnetite) barite, zircon, and garnet, relative to such minerals of low specific gravity as gravity samples are not altered significantly.

No frequency counts were made of heavies obtained by recentrifuging the lights of the centrifuged samples. It is probable that high specific gravity minerals also are deficient relative to low specific gravity minerals in these recentrifuged heavies. The weight of such heavies is very small, however, being about 0.3 per cent of the total weight of heavies in three of the four samples. Much greater differences than this result from sampling or laboratory errors. For all practical purposes, therefore, centrifuge separation may be considered equally effective for all minerals.

TABLE 3. *Number frequencies of representative centrifuge, gravity, and "gravity followed by centrifuge" heavy mineral separates.*

Mineral	#1			#5			#7			Av. all samples		
	C	G	GC	C	G	GC	C	G	GC	C	G	GC
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Ilmenite[1]	31.9	27.6	16.7	28.6	26.4	3.1	31.2	33.8	1.5	30.0	28.6	7.5
Pyroxene[1]	6.2	3.4	4.7	7.8	8.6	6.6	5.0	7.6	5.4	6.4	6.5	5.4
Hypersthene[1]	1.9	1.7	1.3	1.3	1.2	.9	.5	1.7	.5	1.5	1.4	.9
Blue-green hornblende[1]	5.1	5.1	8.7	5.9	7.1	6.1	9.3	5.1	7.9	6.4	6.3	7.5
Green hornblende[1]	2.6	3.1	5.7	5.6	4.0	6.4	5.8	3.4	4.2	5.6	4.9	5.4
Brown hornblende[1]	1.1	2.3	2.3	1.9	.6	1.2	.5	1.4	2.2	1.5	1.6	1.9
Epidote	6.0	4.8	7.7	5.9	6.8	3.5	6.4	4.5	5.9	5.1	6.1	4.9
Tourmaline[1]	1.6	2.3	1.7	2.7	1.8	2.4	1.6	1.1	2.0	2.2	1.9	2.2
Zircon[1]	1.6	1.4	.7	.8	.6	.0	.8	1.7	.5	1.7	1.6	.6
Micas	.0	.3	.0	.8	1.2	3.1	.3	.3	8.4	.5	.7	3.7
Apatite[1]	2.2	3.1	5.3	3.2	1.5	2.1	.5	2.2	1.2	2.2	2.4	2.4
Garnet[1]	1.9	2.0	.3	.8	1.2	.9	1.6	2.0	.0	1.7	1.9	.5
Titanite	1.6	1.7	1.7	1.9	2.2	.2	.8	1.4	.0	1.7	1.6	.8
Barite	1.6	.6	1.0	.0	2.4	.0	.8	.9	.0	1.0	1.0	.3
Diopside[1]	1.1	.9	1.3	.8	1.2	.7	.8	1.7	.7	1.1	1.2	.9
Altered	14.3	15.6	21.7	17.1	21.8	39.4	22.5	18.3	34.4	17.1	18.7	32.2
Rock fragments	7.3	5.1	11.3	5.9	6.1	18.9	6.1	8.2	20.5	6.5	6.0	17.4
Calcite	.3	2.3	1.7	.0	.0	1.4	.3	.0	1.2	.1	.4	1.2
Quartz and feldspar	4.1	11.1	3.0	4.5	.9	.5	.8	1.4	1.5	2.5	2.7	1.8
Unknowns and others[2]	8.0	5.4	3.3	4.5	4.3	2.6	4.2	3.3	1.7	5.4	4.7	2.5
Total	100.0	99.8	100.1	100.0	99.9	100.0	99.8	100.0	99.7	100.2	100.2	100.0
Number of grains counted	370	353	300	374	326	424	377	355	404	3,003	2,781	1,529

[1] Minerals used for chi-square test of significance
[2] Includes small amounts of leucoxene, monazite rutile, staurolite kyanite, and sillimanite

hornblende, pyroxene, apatite, and tourmaline. If the original gravity separations had been equally effective for high and low specific gravity minerals, the relative frequencies in the "gravity followed by centrifuge" separates and in the gravity separates should be essentially the same. Inasmuch as the differences in frequencies exceed the variations that might be caused by sampling errors, the effectiveness is not the same, the separation of low specific gravity minerals being less complete. The amount by weight of such heavies is small, however, and in consequence the number frequencies in the

In this experiment about 5–6 grams of sand, ranging from .124–.088 mm. in diameter and containing about 3.7 per cent of heavies by weight, were used. What effect would a difference in amount of sand, size of grain, or per cent by weight of heavies have had on the rela-

tive efficiency of the two methods? Theoretically, both methods should give equally good results regardless of these factors if (1) the settling time is sufficiently long, (2) convection currents are controlled, and (3) the sand is stirred frequently and thoroughly to eliminate air bubbles and to give each grain an opportunity to settle without interference from other grains. In practice, all three conditions probably are never satisfied completely for either gravity or centrifuge separation. In consequence, the recovery of heavies by both methods will be less complete as the amount of sand is increased, the size of grain decreased, and the per cent by weight of heavies decreased. Also, the effectiveness of gravity settling in comparison with centrifuge separation will be lower as the amount of sediment increases, and as the size of grain and the per cent of heavies decreases. The difference in effectiveness should be greatest for minerals of low specific gravity. Other experiments are needed to test these conclusions.

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PETROGRAPHIC MICROSCOPE SLIDES OF DETRITAL MINERAL GRAINS

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Slides of selected detrital grains are of distinct advantage for student work on heavy minerals. The practicability of such slides depends on placing a few grains of each mineral in rows within the field of view of the medium power. Close spacing aids comparison and the row arrangement aids in working from grain to grain under high power.

To the writer's knowledge slides of this description are obtainable only in England (Milner, 1929). Nowhere has he found satisfactory information on mounting grains in a prearranged pattern. Recently, at the University of Chicago, the writer was able to make several sets of such slides, illustrating the common heavy minerals.

To obtain the proper minerals for mounting, source sands were first sieved to the desired size and then studied in an oil mount to determine the minerals present, their chracteristics, and relative abundance. The initial picking was done from the dry sand spread on a glass plate under binoculars. If abundant, grains of a particular mineral were moved to one part of the plate with a needle point. If rare, they were picked out with a moist camel's-hair brush. A final check on determination was made under a petrographic microscope before placing the grains in labeled bottles.

Hornblendes and diopsides are difficult to determine under the binoculars; but they can be separated from most other minerals. Even under the microscope, when not mounted in oil, their color is too dark for easy distinction, but when placed in a drop of alcohol, they can be quickly distinguished and separated with a needle point. Shortly the alcohol evaporates and the two minerals remain clean, dry, and separate.

The characteristic features of some minerals, especially actinolite, olivine and zoisite, cannot be seen unless these minerals are mounted in oil. Thus, oil mounts must be made of the source sands. Once these particular grains are determined, they can be moved out of the oil with a needle, and the remaining oil and minerals can be wiped away. The selected grains have an oily coating, but if moved through a drop of alcohol, the oil is removed.

In order to mount the grains, the center of each slide was painted with a very dilute solution of gum tragacanth. The grains were then placed in the desired pattern with the aid of a moist camel's-hair brush. The slides were checked with a microscope for accuracy of determination and alignment. Then balsam was put over the grains and the slides were placed on a hot plate. The balsam was cooked and the cover glasses were placed without danger of disturbing the grains. In finished slides, the gum tragacanth is not detectible and it in no way alters the optical properties of the minerals.

When arranging the minerals, the glass slides can be placed on a grid in order to insure uniform pattern and alignment. A grid on black paper for light minerals and white paper for dark minerals is advantageous.

Micas, when being mounted, tend to trap air under them. This is difficult to avoid, but it is helpful to slide the grains into position before the gummed surface has dried.

Caution must be used when placing the cover glass over highly spherical grains such as the St. Peter quartzes and tourmalines, or the glacial apatites. Such grains have a small surface of contact with the slide and, therefore, they move

easily as the cover glass is lowered.

There are various uses for this method of mounting grains. For instance, slides can be made to show the mineral suites of various sandstones, beaches, or drainage basins. Other slides can be made to show the variation in color, shape and surface texture of some one mineral species, or to show zonal growth or secondary enlargement. With a little more care many grains can be so oriented as to give an interference figure. For classes in optical studies crushed minerals can be selected and grains mounted to show stages in relief or birefringence.

The writer wishes to acknowledge the work of Edwin Kurk, who shared in the development of these techniques.

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FIG. 1, AUGUST, 1942

RATE AT WHICH FORAMINIFERA ARE CONTRIBUTED TO MARINE SEDIMENTS

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ABSTRACT

Methods used for the first time in the study of the Foraminifera are yielding results that are of interest to students of biology and geology by establishing the rate of reproduction, the probable rate at which the tests are contributed to the sediments, and the rate of sedimentation in the sea. Statistical studies are being made from samples taken with a special dredge, the population per unit area from samples obtained with a new type of suction grab, and core samples are used to determine the vertical distribution of tests in the sediments.

Before me are a number of samples of marine sediments both recent and geologic. The principal biotic constituent of these samples of mud, sand, shale, and limestone are the tests of Foraminifera. To a geologist, the presence of these tests would probably denote conditions of sedimentation in recent and ancient seas, or the passage of vast intervals of time, while a biologist would consider these skeletal remains in terms of the life activities of the animals that had produced them, and the conditions under which they had lived. The fossilized tests of Foraminifera have proven a valuable aid in tracing oil bearing formations and it is largely because of this that they are now studied more intensively than any other group of Protozoa. In recent years, biologists have described the plan of the life cycle in a number of species. It remains to be determined so far as possible those conditions in the sea which limit the distribution of species, and the rate at which the tests are contributed to the sediments, in order that the paleoecologist may have a better basis for interpreting the biotic conditions in ancient seas and the duration of geologic horizons.

The enormous numbers of benthonic Foraminifera found at shallow and intermediate depths, the relative uniformity of conditions over considerable areas on the floor of the sea, and the fact that these organisms live and die within a matter of inches or a few feet at the most of the place of origin, make this group a most favorable material for the study of populations. Vast numbers of living Foraminifera may be taken with a special dredge consisting of a plankton net provided with four light metal runners somewhat longer than the net and attached to a ring at right angles to one another so that no matter in what position the dredge arrives at the bottom, it will rest on two of the runners and support the net a few inches above the sediments (fig. 1, b). Attached to the bridle of the net is an iron rod 6 feet in length with a 6 foot length of one inch chain attached to the opposite end. As the chain drags on the bottom, the surface sediments, including the Foraminifera, are thrown into suspension, and are caught in the net as it moves forward. By carefully adjusting the distance between the chain and the net, depending upon the speed of the boat and the nature of the bottom, an amazing proportion of the Foraminifera taken will be found to be living.

When a foraminifer is killed in alcohol and the test dissolved with acid, the resulting protoplasmic cast provides a convenient means for distinguishing microspheric from megalospheric individuals and for determining the number of chambers in the test which is indicative of the degree of maturity of the individual.

After these protoplasmic casts are treated with biological stains and cleared in oil, it is possible to recognize individuals that were about to reproduce from the conditions of the nuclei. It is also possible to distinguish those that were feeding actively from the food organisms contained in the protoplasm that filled the test and those that were in a dormant condition from the excessive amount of shrinkage in the protoplasmic cast of the chambers.

When the number of chambers in samples of 500 or more Foraminifera of the same species are plotted as percentage frequency distribution curves for each month in the year, it is possible to determine the rate of growth both in the microspheric and megalospheric generations, as well as the life span of each, and from the relative abundance of juvenile and adult individuals at different seasons, the time and intensity of reproductive activities. The possible rate of increase in the Foraminifera may be determined from the number of megalospheric juveniles asexually produced by microspheric agamonts maintained in cultures which is probably the same as the number produced in the sea, and the ratio of microspheric to megalospheric tests found in the sediments, for although each megalospheric gamont produces from hundreds to tens of thousands of

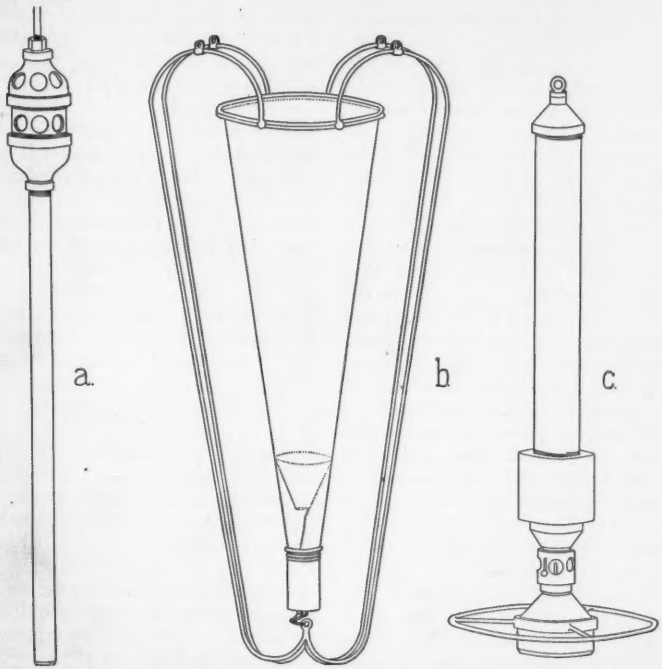

FIG. 1.—(a) Trask coring tube used to determine the vertical distribution of Foraminifera in the sediments. (b) Special dredge for taking living Foraminifera for population studies. (c). Suction grab for determining the population of foraminifera per unit area on the floor of the sea.

gametes, depending upon the species and the size of the individual, the chances of two gametes becoming fertilized and the resulting zygote surviving to produce a microspheric juvenile of sufficient size to be recognized is relatively negligible compared with the chances of survival of a preformed megalospheric juvenile. From the rate of reproduction and the number of generations produced annually, the potential productivity of the species can be determined (Myers, 1942).

The method we have used in determining the population of Foraminifera per unit area on the floor of the sea includes taking a sample of surface sediments 10 cm. in diameter with a new type of suction grab (fig. I, c).This grab consists of a long compression chamber provided with a delivery tube that empties into the upper portion of the chamber and is closed at the lower end by a glass disc. The disc is held in place by heavy grease and a tubular brass sleeve provided with ports in which the smaller end of a funnel shaped sampling device slides freely in such a manner that the ports are closed when the grab strikes the bottom and at the same moment a plunger smashes the glass disc. The air in the chamber is compressed by the inrush of a watery sample of surface sediments driven through the delivery tube into the chamber at a pressure that is equal to the weight of the column of water above the bottom. As the grab is hauled to the surface the sample is not subjected to washing nor can it otherwise escape as so often happens with other sampling devices, particularly when the sample consists of coarse sand or there is an appreciable amount of shell fragments or other coarse material in the sediments. The grab is so constructed that an optimum sample is taken in 10 meters of water. At greater depths the volume of the sample is controlled by placing an amount of water in the chamber that is equal to the difference between the volume of the sample desired and the volume of water that would enter the chamber at the depth the sample is taken. The grab is prevented from sinking too deeply into the bottom by a wide ring supported by radiating rods attached to the funnel shaped head. After the sample is removed it is washed in a tubular sack made of bolting silk with 125 openings to the inch. This sack retains the smallest foraminifer and allows the clay and silt particles to be washed from the sample. The sample is then treated with a 10 per cent aqueous solution of formalin at 65° C., and stored for future study. The Foraminifera in these samples will retain their color for weeks or even months, and it is possible from the color of the protoplasm that shows through the walls of the test of many species to recognize those animals that were living when the sample was taken, otherwise it is necessary to dissolve the tests with acid and stain the protoplasmic cast with biological stains. In making population determinations only a well mixed quarter of the sample is used.

In the shallow and intermediate depths of the sea, seasonal variations in the life activities of most organisms are comparable in intensity to those observed in the fauna of the adjacent coast. In the middle and higher latitudes reproduction in many Foraminifera is limited to the spring months, therefore, juvenile stages of these species are most numerous at this season, whereas the majority of individuals taken in the fall are approaching maturity. In a species that develops a test consisting of approximately 40 chambers, the majority of individuals taken in the fall will have from 20 to 40 chambers. Should we find that the population of such a species is 1,000 individuals per square meter and in a well mixed sample of subsurface sediments 45 per cent of the empty tests of this species fall within the size groups of from 20 to 40 chambers, it is evident that at least 55 per cent of the individuals had died before reaching this growth limit. Therefore, the number of tests contributed to the sediments by this species on that particular year would approximate the

sum of the two groups, or about 2,222 individuals per square meter. If 10 per cent of the empty tests of all species found in the sediments belonged to the species in question, then the total number of tests contributed to the sediments by all species would be 10 times 2,222 or 22,220.

Should the upper 30 cm. of sediments taken with a coring tube 4 cm. in diameter (fig. 1, a) contain a total of 250,000 tests and the annual rate at which these tests were contributed to the sediments was 22,220 per square meter, or 27.7 to the 12.5 square cm. of sea bottom sampled by the coring tube, then the rate of deposition of the shells of Foraminifera in the region under discussion would be equal to 250,000, the total number of tests in the samples, divided by 27.7, or about 9,000, which is the number of years that would be required for the accumulation of 30 cm. or approximately 1 foot of sediment if no tests were destroyed by mud eating organisms, or other agencies. Should the above computation be made for two or more species, the results should be comparable, otherwise it is probable that one of the species selected produces more than one generation annually, or the tests of the species were destroyed at different rates, although the latter is easily guarded against by selecting species having tests of similar size and composition.

Foraminifera usually terminate their existence in one of three ways. They either reproduce, are ingested as food by larger organisms or become buried in the sediments as a result of turbulence or current action to depths from which they are unable to escape. Where strong currents prevail the tests become eroded and under certain conditions in the sediments chemical decomposition of the tests takes place. However, the abundance and splendid preservation of the most minute and fragile tests in the majority of samples of recent sediments suggest that these agencies seldom destroy even these in appreciable numbers. This conclusion is further supported by the state of preservation of the tests of Foraminifera observed in the faeces of a number of groups of invertebrates. This work will be repeated in regions where there is relatively little calcium carbonate in the sediments.

Maximum populations of "living" Foraminifera observed by us range from 31,980 per square meter on a sandy bottom in Plymouth Sound, Plymouth, England, to more than 1,000,000 per square meter on a bottom covered with moss-like growths of algae of a submerged reef opposite Sanoer on the island of Bali in the Netherlands East Indies. The number of tests in 1 gram of the sieved fraction of 2–0.2 mm. diameter of *Globigerina Ooze*, according to Schott, is slightly over 12,000. The total number of tests in 1 cc. of wet sediment from the eastern end of the Java sea was in excess of 39,000, a number that is not unusual for the mud bottoms of the region because of the many minute species. In a later paper, we will present data as to the probable rate of sedimentation in specific regions as determined from the Foraminifera and attempt to explain the influence of measurable ecological conditions upon the rate at which these protozoa contribute to the sediments. This work is being continued with the aid of a grant from the Penrose fund of the Geological Society of America.

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